18EE8732:Micro and Nano Scale Sensors and Transducers

MODULE – 1:Pressure Sensors

Prepared By,
Shreeshayana R
Electrical and Electronics Engineering
ATME College of Engineering, Mysuru

CONTENTS

- Course Overview

Course Credit Description:

SL.No.	Course Code	Course Type	Course	Teaching Hours /Week	Exam Duration in Hours	Theory Marks	I.A Marks	Total Marks	Credits
1	18EE8732	Core	Micro and Nano Scale Sensors and Transducers	4	3	60	40	100	3

Prerequisites:

SL.No.	Course Name	Module / Topic / Description
1	Electrical & Electronics Measurements and Instrumentation	Sensors and Transducers
2	Operational Amplifiers	Amplifier types
3	Basic Electrical Engineering	Sensors

Course Delivery:

Duration	Wee1 to Week 3:
Module 1: **Pressure Sensors**	Capacitive Pressure Sensors, Inductive Pressure Sensors, Ultrahigh Sensitivity Pressure Sensors. [L3]

Duration	Week 3 to 5:
Module-2: **Motion and Acceleration Sensors** **Gas and Smoke Sensors**	**Motion and Acceleration Sensors:** Ultrahigh Sensitivity, Wide Dynamic Range Sensors, Other Motion and Acceleration Microsensors. **Gas and Smoke Sensors:** A CO Gas Sensor Based on Nanotechnology, Smoke Detectors.

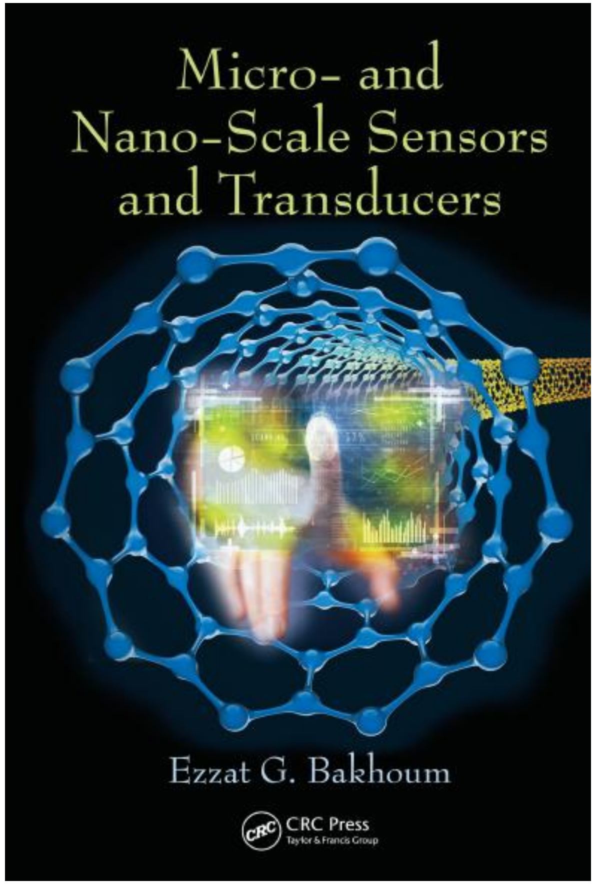
Learning Resources prescribed by University:

1. Micro- and Nano-Scale Sensors and Transducers, By Ezzat G. Bakhoum,CRC Press, 1st Edition,2015.

Additional List of URLs, Text Books, Notes, Multimedia Content, etc

1. Electrical and Electronic Measurements, R.K Rajput, S. Chand, 3rd Edition, 2013
2. A Course in Electronics and ElectricaL, J.B. Gupta, Katson Books, 13th Edition, 2008
3. A Course in Electrical and Electronic Measurements and Instrumentation, A. K. Sawheny, DhanpatRai, 2015

Learning Resources prescribed by University:

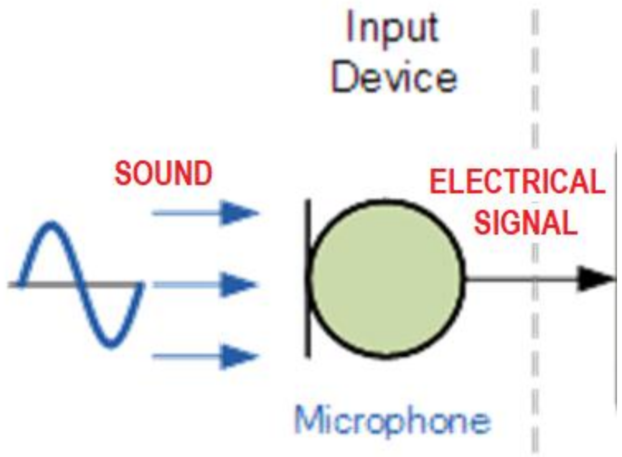


COURSE OBJECTIVES:

1. To explain the measurement of pressure using sensors, based nanotechnology, their structure, theory of operation.
2. To explain structure, theory of operation of sensors based on nanotechnology for Motion, acceleration, measurement, gas and smoke detection.
3. To explain sensors based on nanotechnology for the measurement of atmospheric moisture and moisture inside the electronic components.
4. To explain Optoelectronic and Photonic Sensors used in optical microphones, fingerprint readers, and highly sensitive seismic sensors.
5. To explain the structure, operation of Biological Sensors, Chemical Sensors, and the so-called "Lab-on-a-Chip" sensors used in multipurpose biological and chemical analysis devices and Electric, Magnetic, and RF/Microwave, Integrated Sensor/Actuator Units and Special Purpose Sensors driven by nanotechnology.

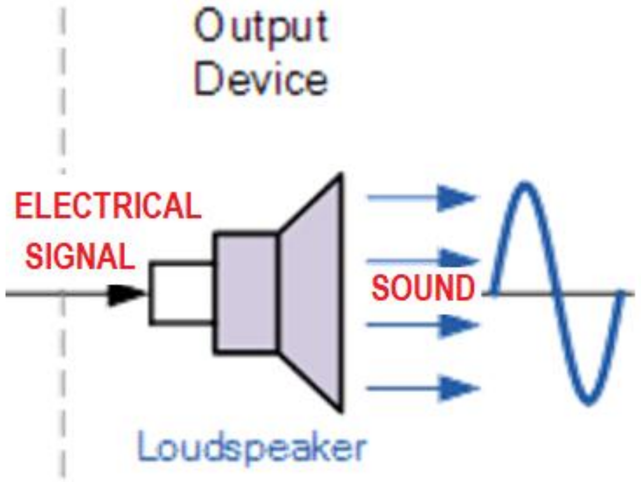
SENSOR -DEFINITION

- A **sensor** is a device that measures physical input from its environment and converts it into data that can be interpreted by either a human or a machine.
- Most **sensors** are electronic, but some are more simple, such as a glass thermometer, which presents visual data.



ACTUATORS

- An actuator is a device that moves or controls some mechanism. An actuator turns a control signal into mechanical action such as an electric motor.
- Actuators may be based on ***hydraulic, pneumatic, electric, thermal or mechanical means.***



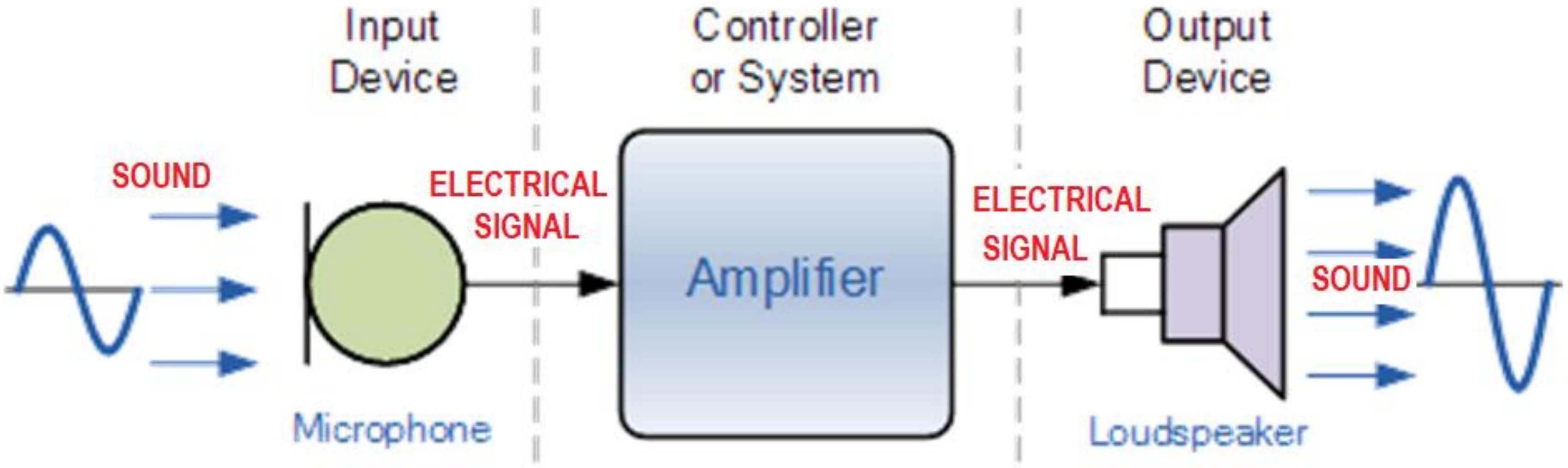
TRANSDUCER

TRANSDUCER = SENSOR + ACTUATOR

Transducers are used to convert energy of one form into energy of another form.

Example, a microphone (input device) converts sound waves into electrical signals and a loudspeaker (output device) converts these electrical signals back into sound waves

SIMPLE INPUT /OUTPUT TRANSDUCER



SENSOR ACTUATOR

A microphone (input device) converts sound waves into electrical signals and a loudspeaker (output device) converts these electrical signals back into sound waves

Significant Parameters which indicate the transducer capability are:

- Linearity
- Repeatability
- Resolution
- Reliability

TERMS RELATED WITH SENSORS

- **ERRORS**

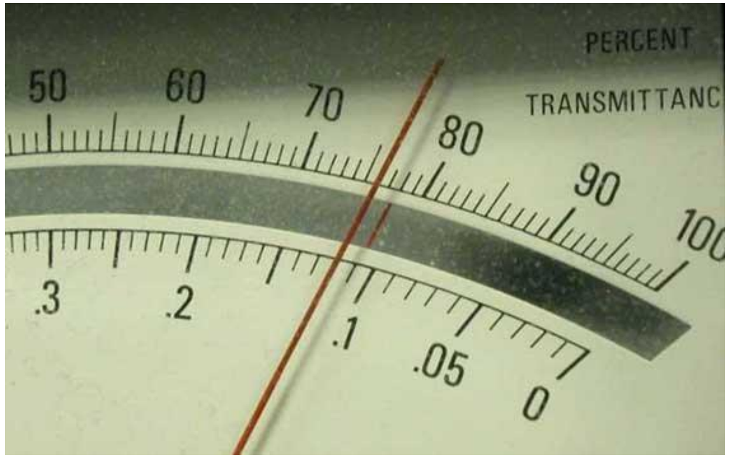
  Gross Error – due to human mistake

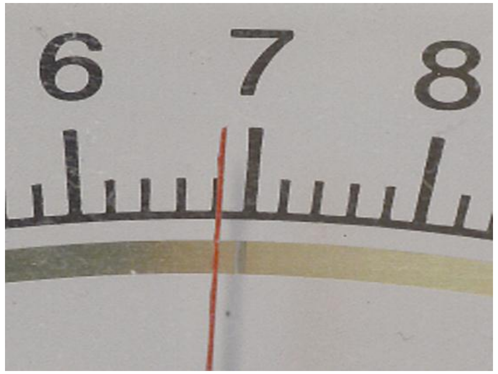
  Systematical Error – Due to instrument, environment

  Random error- Error in measurement like blood pressure

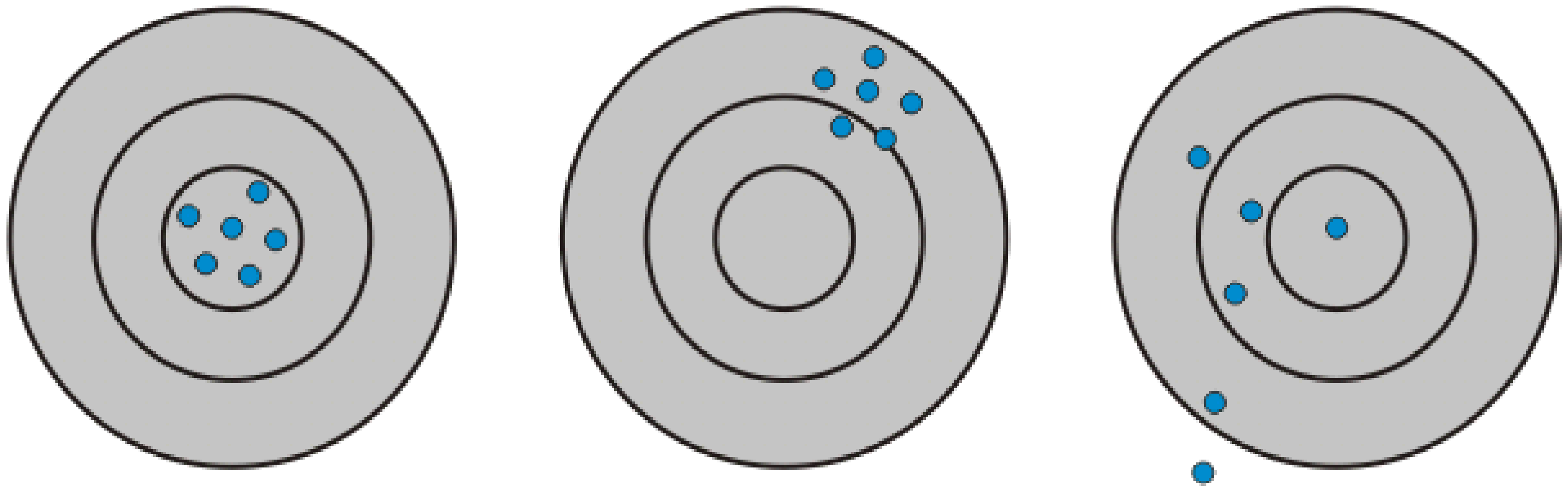
  Absolute error – diff. bet exp. Value – meas. value
- **PRECISION**
- **ACCURACY**

ERROR





PRECISION AND ACCURACY



High Accuracy
High Precision

Low Accuracy
High Precision

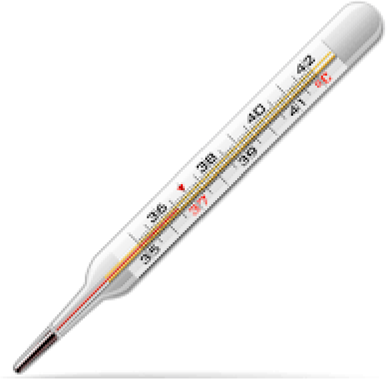
Low Accuracy
Low Precision

SENSORS

- PAST
- PRESENT
- FUTURE

SENSORS IN EARLY DAYS

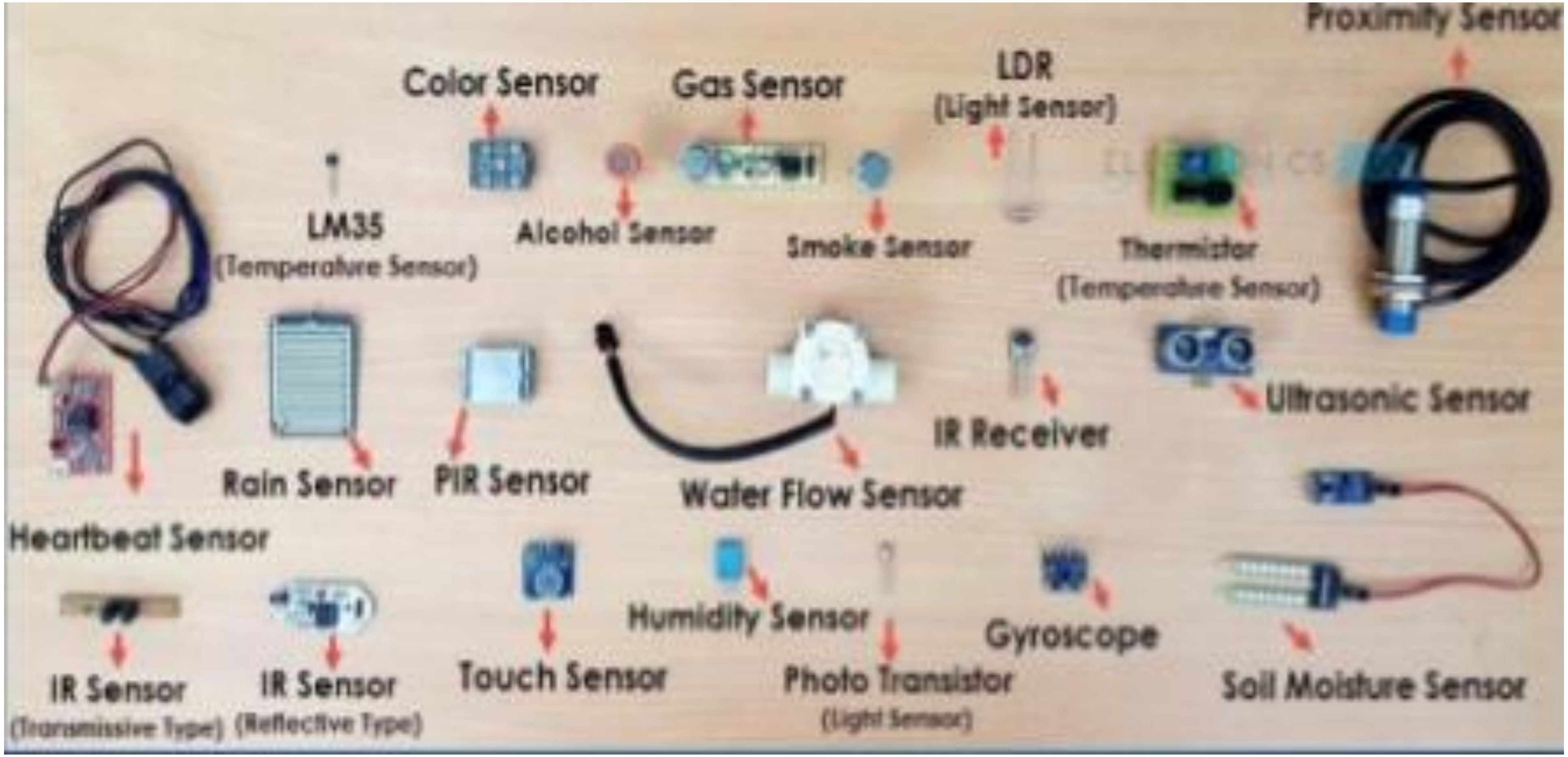
- Glass thermometer
- Thermocouple
- Magnetic compass



Sensors in Present Day

Quantity being Measured	Input Device (Sensor)	Output Device (Actuator)
Light Level	Light Dependant Resistor (LDR) Photodiode Photo-transistor Solar Cell	Lights & Lamps LED's & Displays Fibre Optics
Temperature	Thermocouple Thermistor Thermostat Resistive Temperature Detectors	Heater Fan
Force/Pressure	Strain Gauge Pressure Switch Load Cells	Lifts & Jacks Electromagnet Vibration
Position	Potentiometer Encoders Reflective/Slotted Opto-switch LVDT	Motor Solenoid Panel Meters
Speed	Tacho-generator Reflective/Slotted Opto-coupler Doppler Effect Sensors	AC and DC Motors Stepper Motor Brake
Sound	Carbon Microphone Piezo-electric Crystal	Bell Buzzer Loudspeaker

SENSORS


Proximity Sensor
Color Sensor
Gas Sensor
LDR
(Light Sensor)
LM35
(Temperature Sensor)
Alcohol Sensor
Smoke Sensor
Thermistor
(Temperature Sensor)
Ultrasonic Sensor
IR Receiver
Rain Sensor
PIR Sensor
Water Flow Sensor
Heartbeat Sensor
Humidity Sensor
Gyroscope
IR Sensor
(Transmissive Type)
IR Sensor
(Reflective Type)
Touch Sensor
Photo Transistor
(Light Sensor)
Soil Moisture Sensor

Choosing a sensor

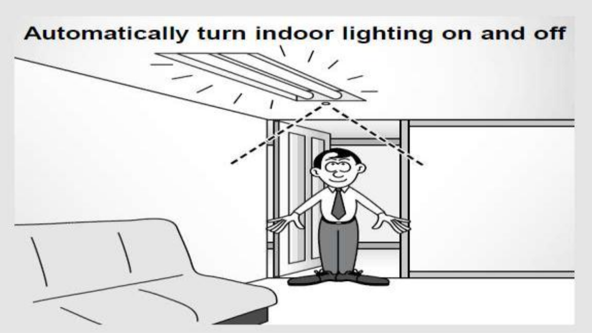
- A dc sensor is one that responds to constant inputs, whereas a *non-dc sensor is unable to distinguish constant* inputs.
- As an example, a piezo accelerometer can sense *changing* acceleration but is not able to sense *constant acceleration*
- there are dc accelerometers that can measure constant acceleration
- the speedometer in your car can respond to *changing speeds, but that does not make it an* accelerometer,
- In choosing a sensor, it is important to determine whether it is dc or non-dc in accordance with your application requirements.

Characteristics of Sensors

- **STATIC CHARACTERISTICS**
  Linearity
  Precision
  Sensitivity
  Resolution
  Hysteresis
- **DYNAMIC CHARACTRISTICS**
  Frequency response
  noise
- **CALIBRATION**

PRESENT DAY SENSORS- MOTION SENSORS

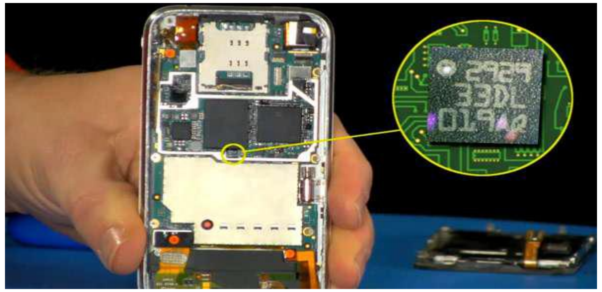
- **IR BASED SENSORS**



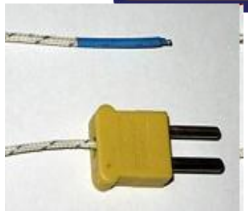
- **ULTRA SONIC MOTION SENSORS**

- **MICROWAVE MOTION SENSING**

- **ACCLEROMETER BASED SENSOR**

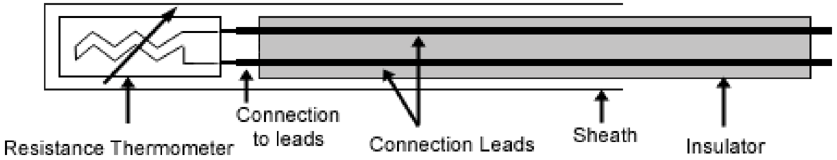


Temperature Sensors

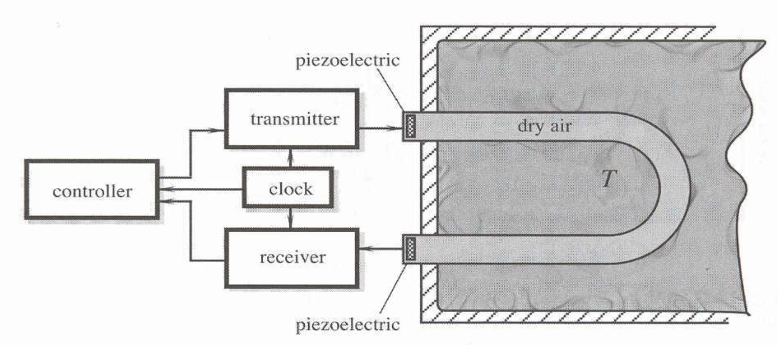


- THERMOCOUPLE

- TEHRMISTORS
- RTD – Resistance Temperature Detectors



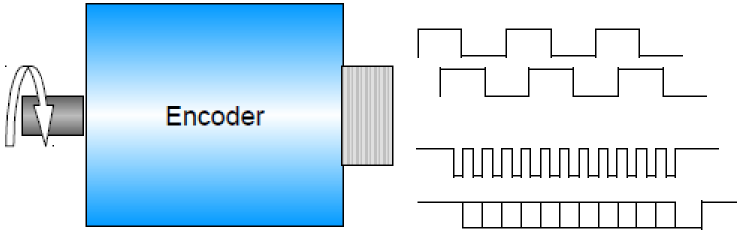
- Acoustic Sensors



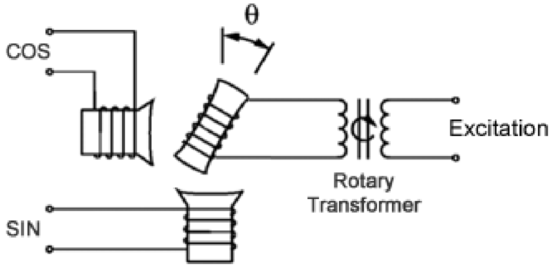
PRESENT DAY SENSORS -POSITION SENSORS

- POTENTIOMETER SENSOR

- ENCODERS

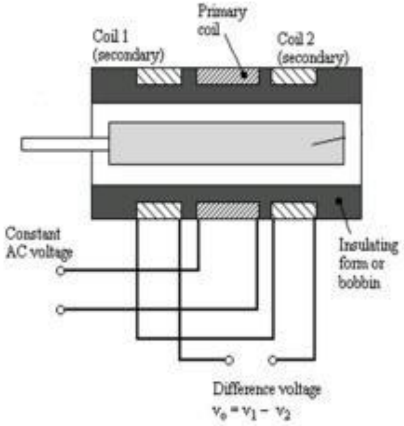


- RESOLVERS



PRESENT DAY SENSORS –DISPLACEMENT SENSORS

- LVDT – Linear Variable Differential Transformer



- RVDT – Rotary Variable Differential Transformer

PRESENT DAY SENSORS -RANGE SENSORS

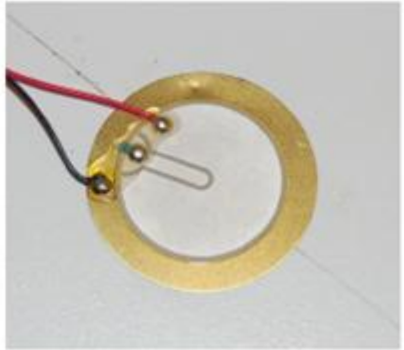
- LIDAR – **LI**ght **D**etection **A**nd **R**anging
- BEACON – uses Bluetooth

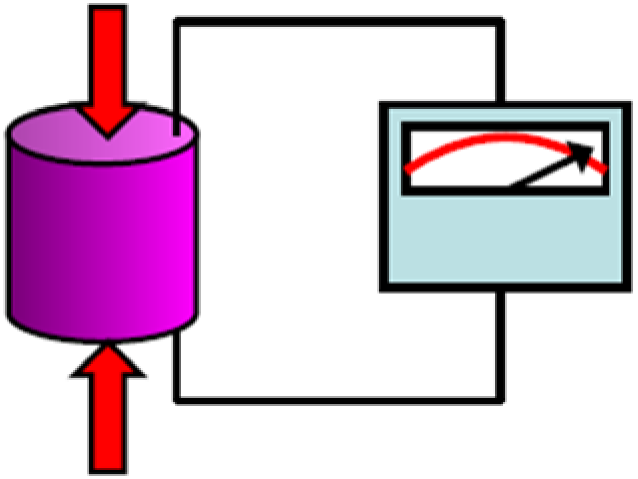
- ULTRASONIC RANGE SENSORS

  Distance, Level, Presence, Diameter, Position

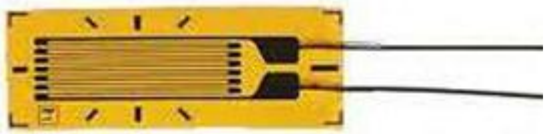
PRESENT DAY SENSORS – PRESSURE SENSORS

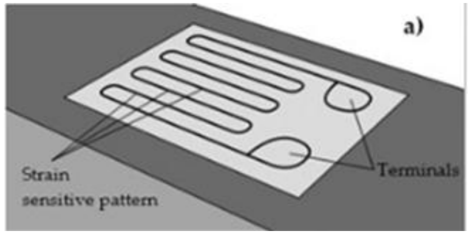
- PIEZO ELECTRIC SENSOR



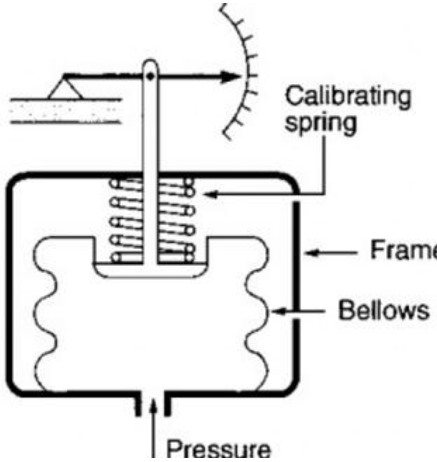


- LOAD CELL/ strain gauge



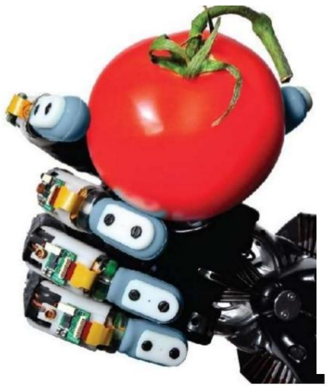


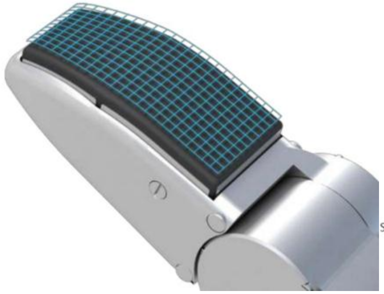
PRESSURE SENSORS

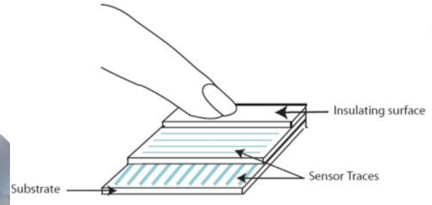


- BELLOW SENSORS

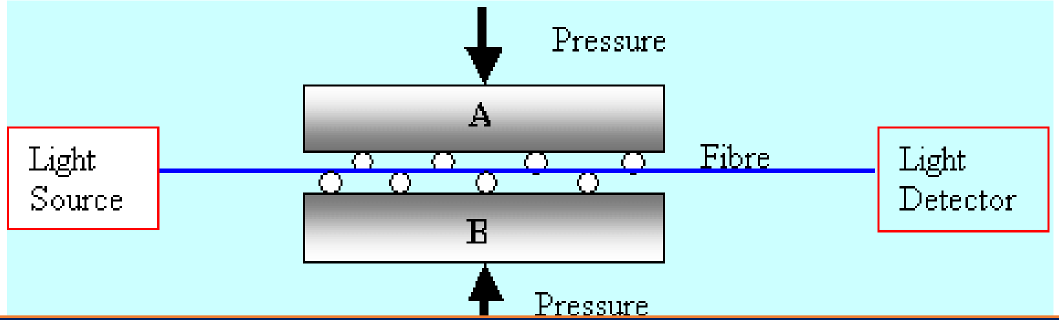
- TACTILE SENSORS





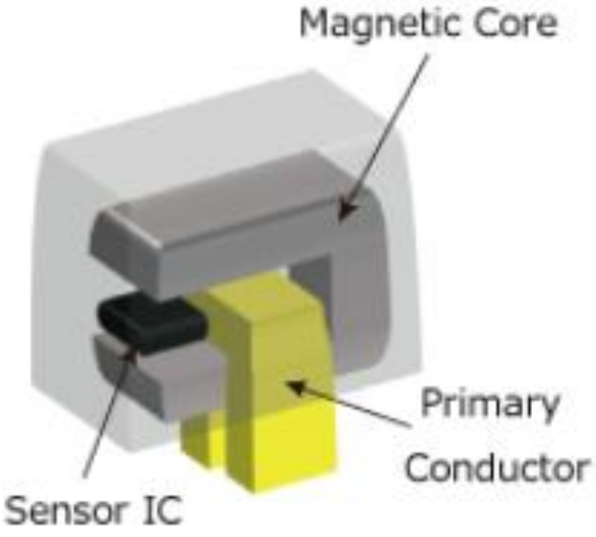


- FIBRE OPTIC SENSOR

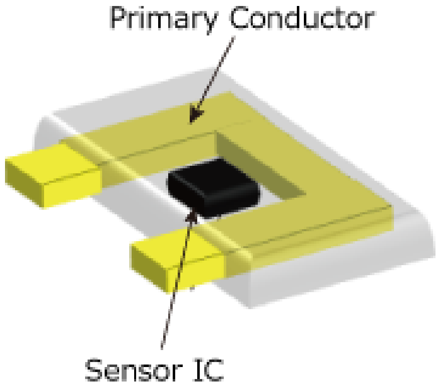


Current Sensors

- CORED SENSOR

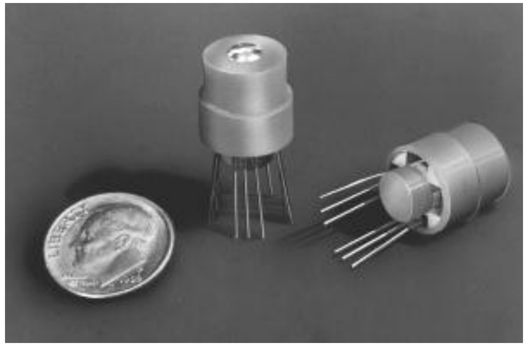


- CORELESS SENSOR

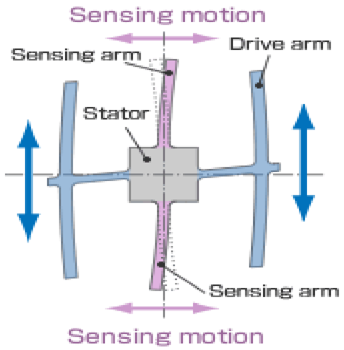


DIRECTIONAL SENSORS

- HEADING SENSOR



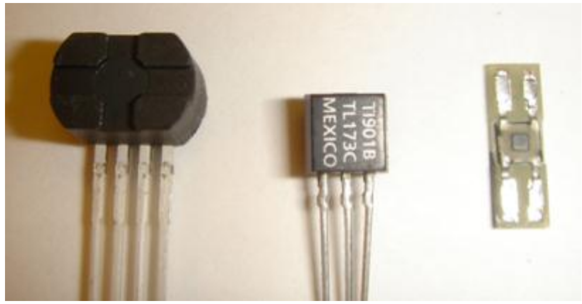
- MAGNETIC COMPASS
- GYRO SENSORS
- INCLINOMETER

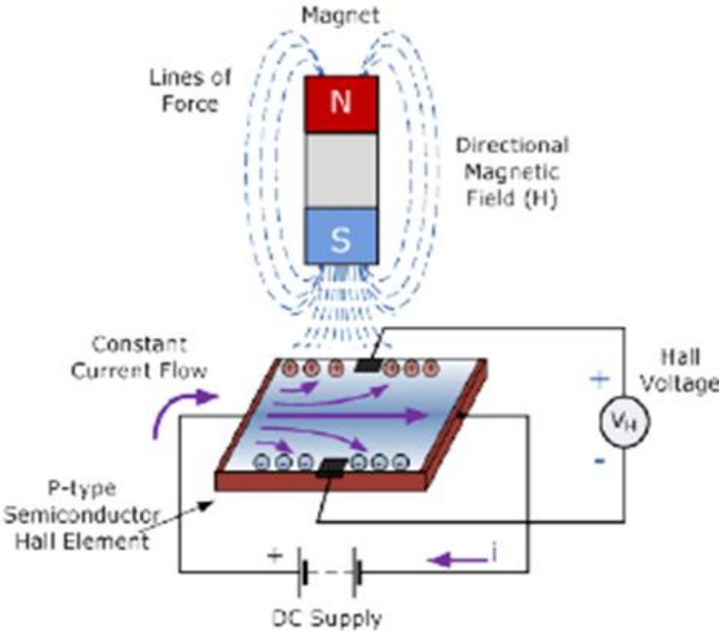


4. The stationary part bends due to vertical drive arm vibration, producing a sensing motion in the sensing arms.

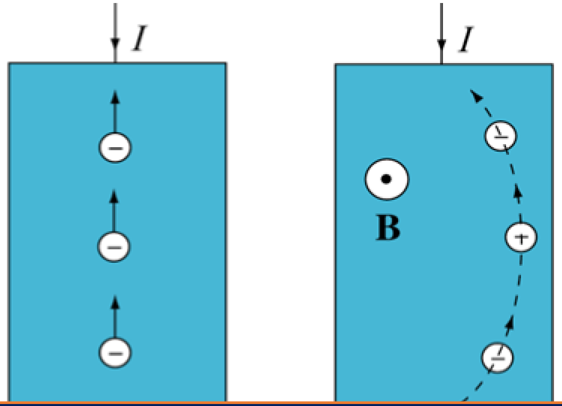
MAGNETIC SENSORS

- HALL EFFECT SENSORS



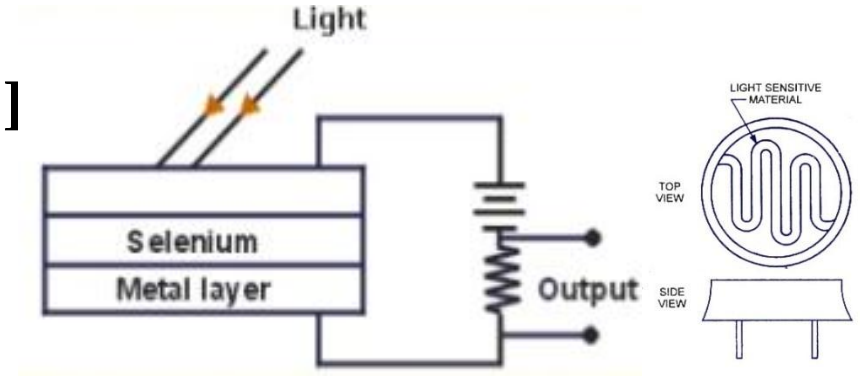


- MAGNETO RESISTIVE SENSOR

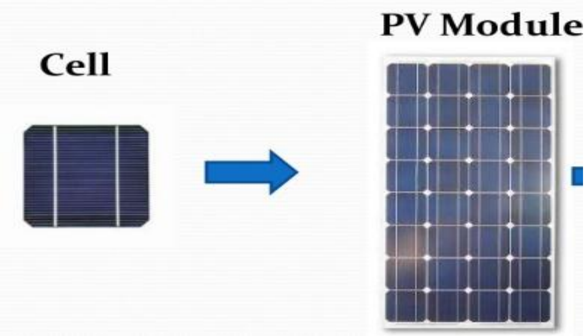


OPTICAL SENSORS

- PHOTOCONDUCTIVE CELL



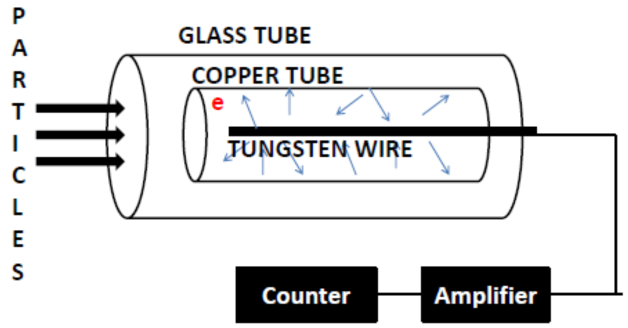
- PHOTOVOLTAIC CELL



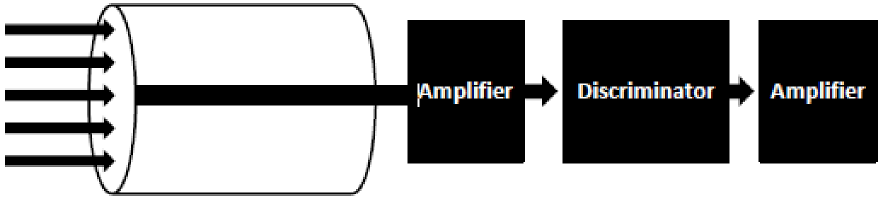
- LDR – Light Dependent Resistor

RADIATION SENSORS

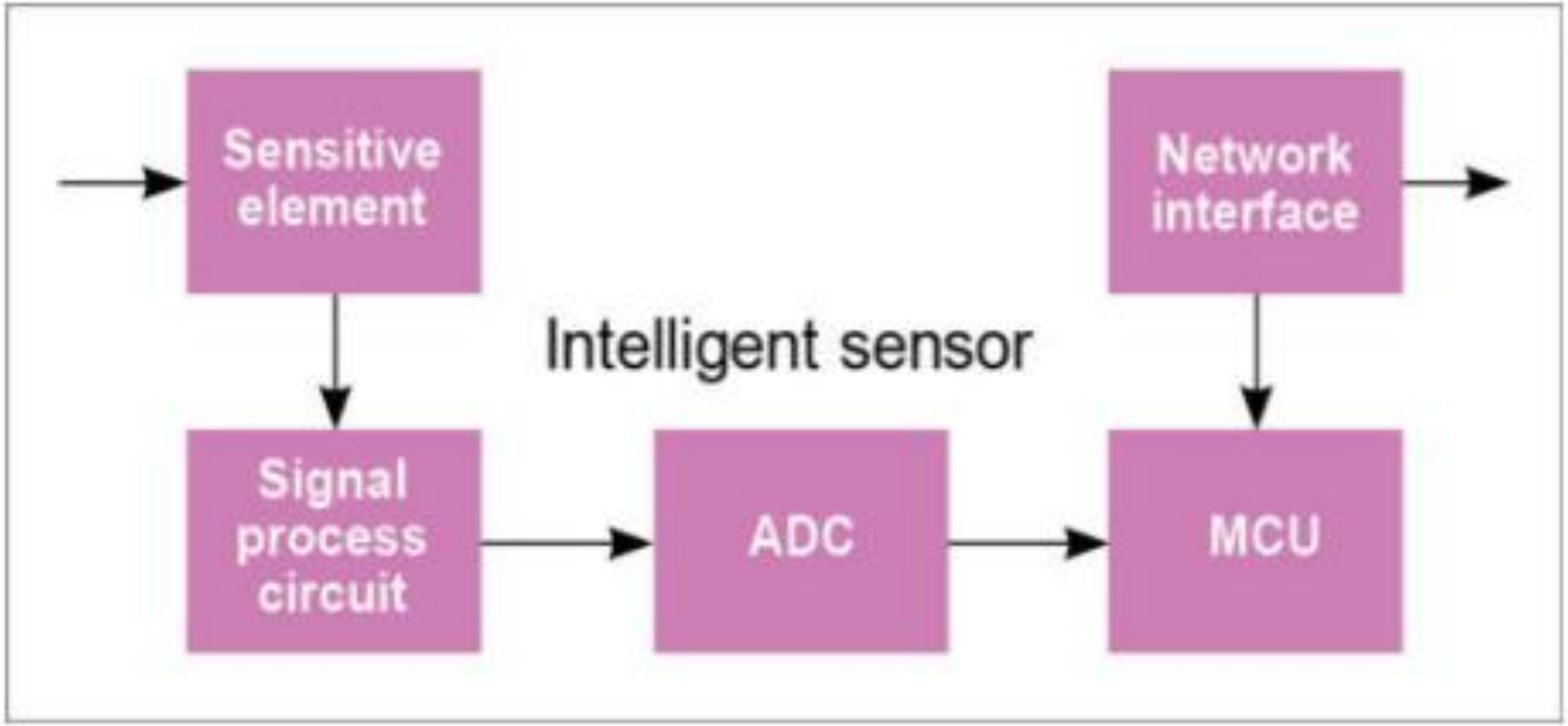
- GM SENSOR Geiger–Müller



- PROPORTIONAL COUNTER



INTELLIGENT SENSOR



LATEST SENSORS

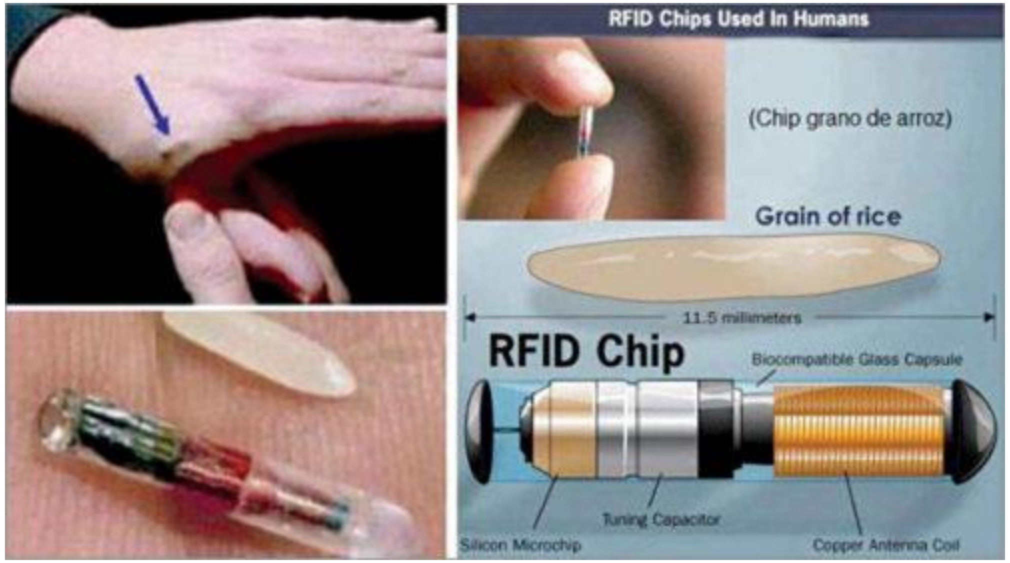
- IoT sensors
- pollution sensors
- RFID sensors
- image sensors
- biometric sensors
- printed sensors
- MEMS and NEMS sensors.

IoT Sensors

- IoT sensors include temperature sensors, proximity sensors, pressure sensors, RF sensors, pyroelectric IR sensors, water-quality sensors, chemical sensors, smoke sensors, gas sensors, liquid-level sensors, automobile sensors and medical sensors.

RFID Chips

- Chips as small as the size of rice grains can be inserted directly under the skin for use as ID cards. There is a trend to use RFID chips in many products including contactless banks cards and Oyster cards. There are also cases where chips are implanted in pets and cattle for monitoring.



WEARABLE SENSORS

- These latest sensors include medical sensors, GPS, inertial measurement unit (IMU) and optical sensors. With modern techniques and miniature circuits, wearable sensors can now be deployed in digital health monitoring systems. Sensors are also integrated into various accessories such as cloths, wrist bands, eyeglasses, headphones and smartphones.

Optical image sensors

- The best example of this sensor is found in your smartphone camera. An image sensor detects and conveys the information that constitutes an image. Digital imaging is fast replacing analogue imaging. Most digital cameras use CMOS sensors, which allow faster speed with lower power consumption.

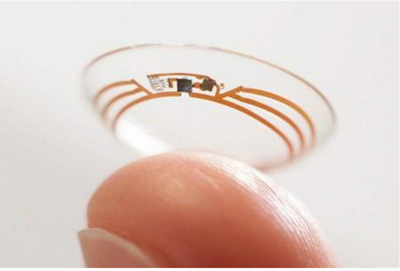
Biometric sensors

- The latest generation of fingerprint sensors from Qualcomm consists of sensors for display, glass and metal, detection of directional gestures, and underwater fingerprint match

PRINTED SENSORS

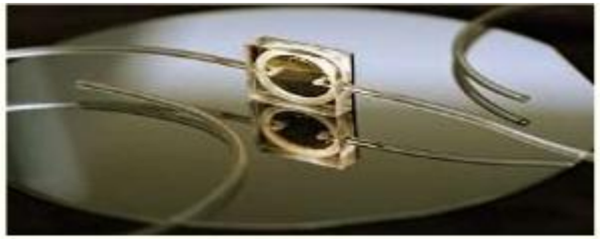
- Sensors printed on flexible substrates are becoming popular. The next generation of printed sensors will enable applications ranging from human-machine interfaces to environmental sensing.

MEMS Applications



Google Smart Contact Gulcometer

Accelerometer Module



Bio-cavity LASER
(Distinguish cancerous cells from non-cancerous cells)

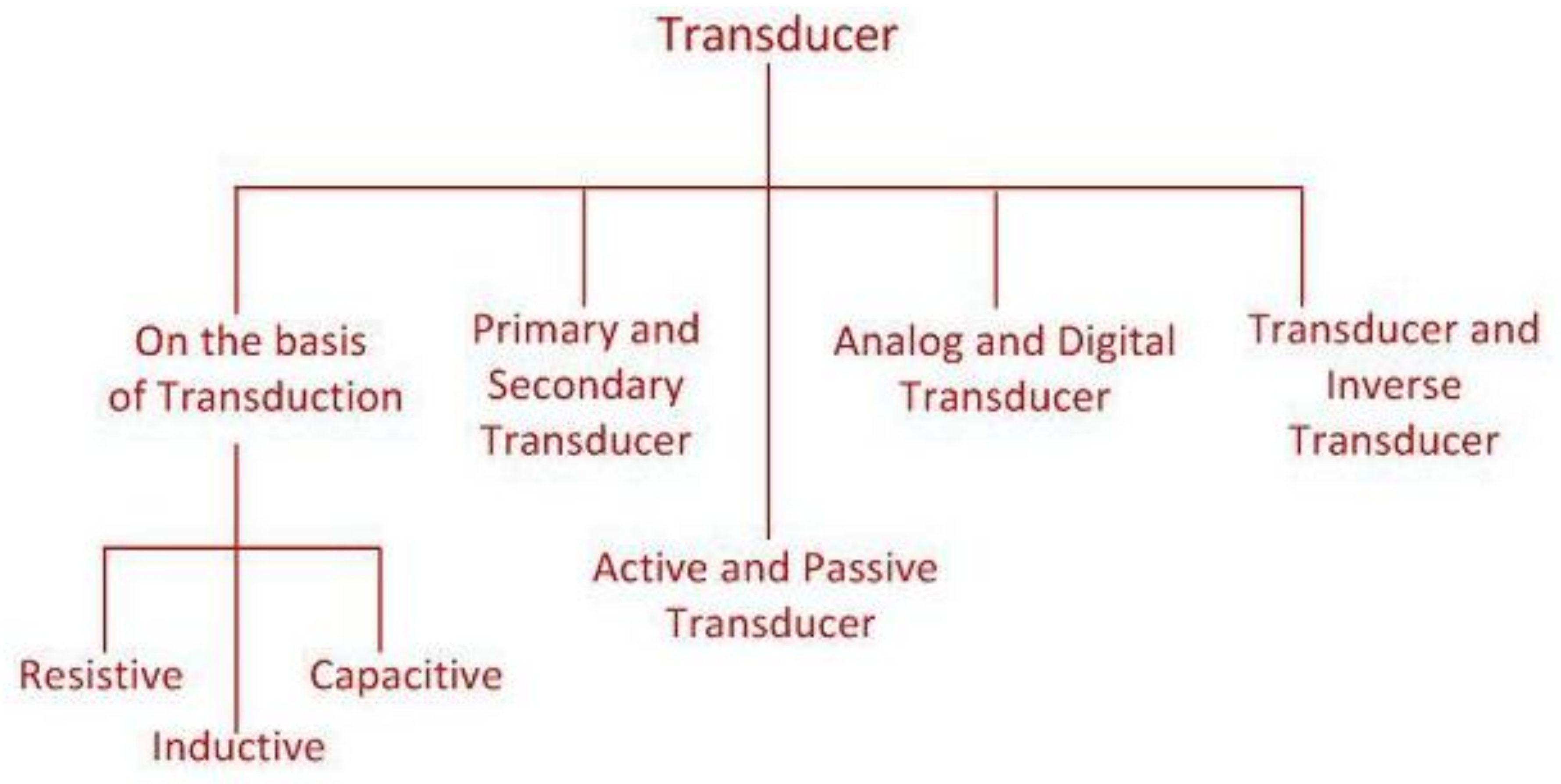
Artificial REtina

- Vehicle Airbag sensor (Accelerometer using MEMS)
- Mobile phone microphones
- Blood Pressure monitors
- Digestible Camera
- ABS system in airbag.

ADVANCED SENSORS

- Wireless pressure sensors
- Particulate matter sensor
- Torque sensor
- Multi-turn absolute encoders

Classification



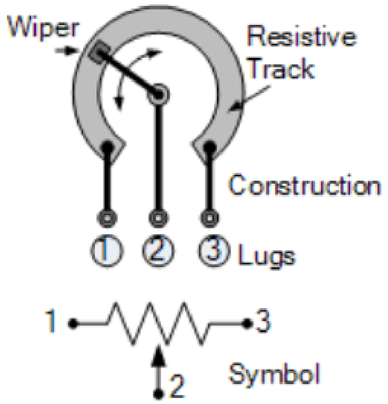
Transducers are classified based on:

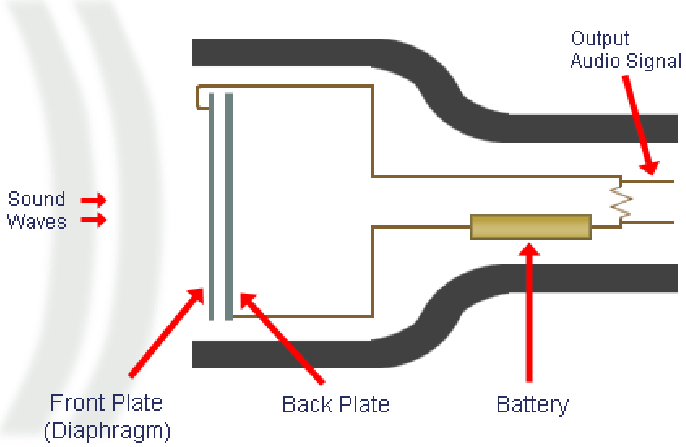
1. On the basis of transduction form used
2. As primary and secondary transducers
3. As passive and active transducers
4. As analog and digital transducers
5. As transducers and inverse transducers

1. Classification based on the principle of transduction form used:

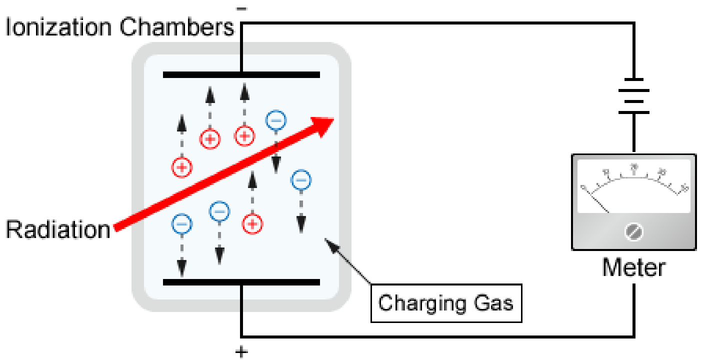
This classification is based on the principle of transduction as resistive, inductive, capacitive etc. depending upon their conversion into resistance, inductance or capacitance respectively. They can be classified as thermoelectric, piezoelectric, electro-kinetic, optical and magneto restrictive.

- **Resistance** - Potentimeter devices, Resistance strain gauge, Pirani guage or hot wire meter, Resistance thermometer, Thermistor, Resistance hygrometer, Photoconductive cell.
- **Capacitance** - Variable capacitance pressure gauge, Capacitor microphone, Dielectric gauge.

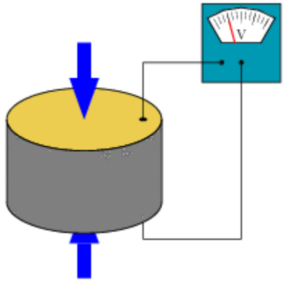




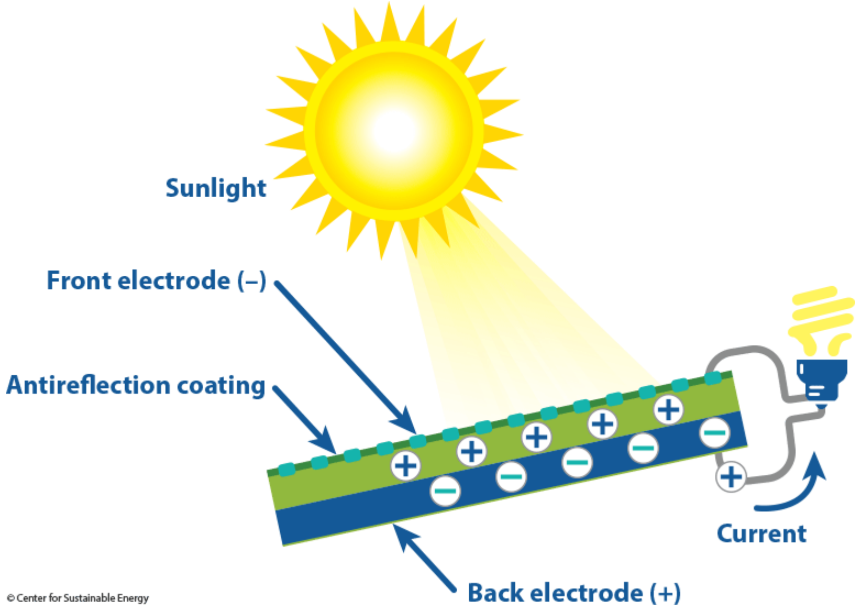
- **Inductance** - Magnetic circuit transducer, Reluctance pick-up, Differential transformer, Eddy current guage, Magneto striction gauge.



- **Voltage & Current** - Hall effect transducer, Ionisation chamber, Photo emissive cell, Photomultiplier tube.



- **Self-generating transducers** - Thermocouple, Thermopile, Moving coil generator, Piezoelectric transducer,
- **Photovoltaic**.

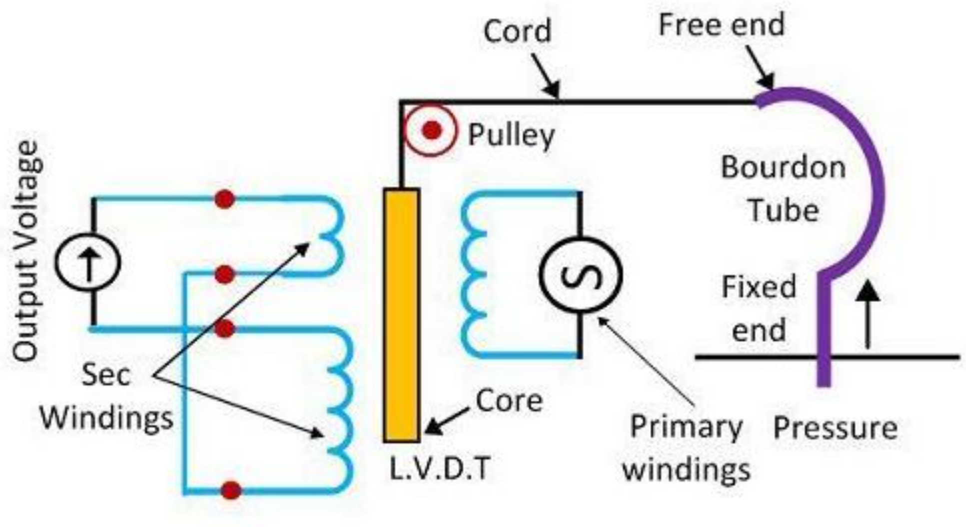


2. Classification as primary and secondary transducers

Primary transducer senses the **input directly and physical phenomenon is converted into the electrical form directly.**

While in secondary transducer, initially input is being sensed by some detector or sensor and then its output in some form other than input signal is given to transducer to convert into electrical signal.

Mechanical device acts as a primary detector transducer and the **electrical device acts as the secondary transducer** in most of the measurement systems with mechanical displacement serving as the intermediate signal.



Bourdon's Tube

Eg: Bourdon's tube and LVDT

First, the pressure is converted into a displacement and then it is converted into the voltage by the help of the L.V.D.T.

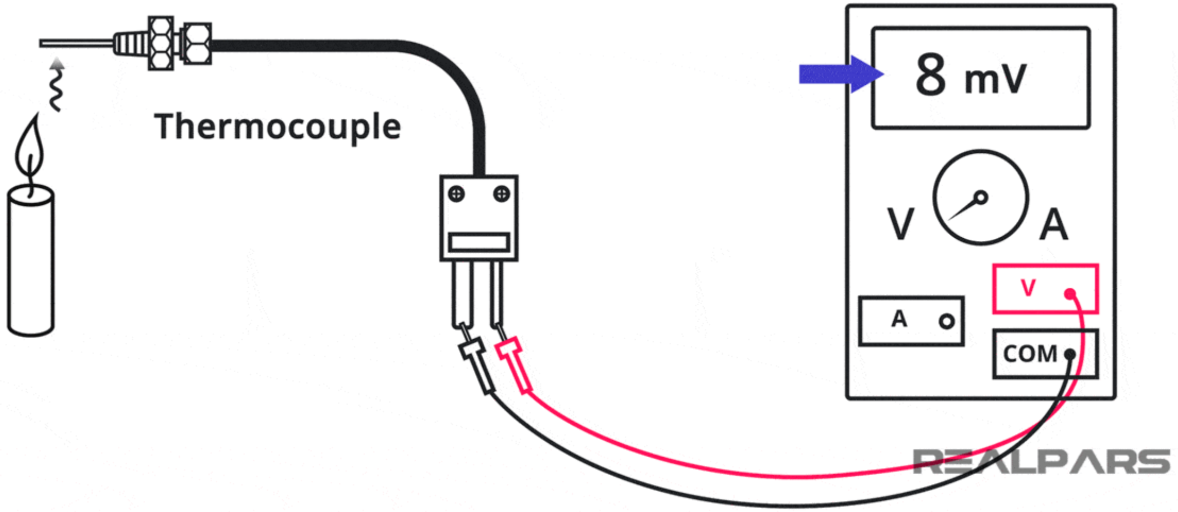
3. Classification as Active and Passive transducer

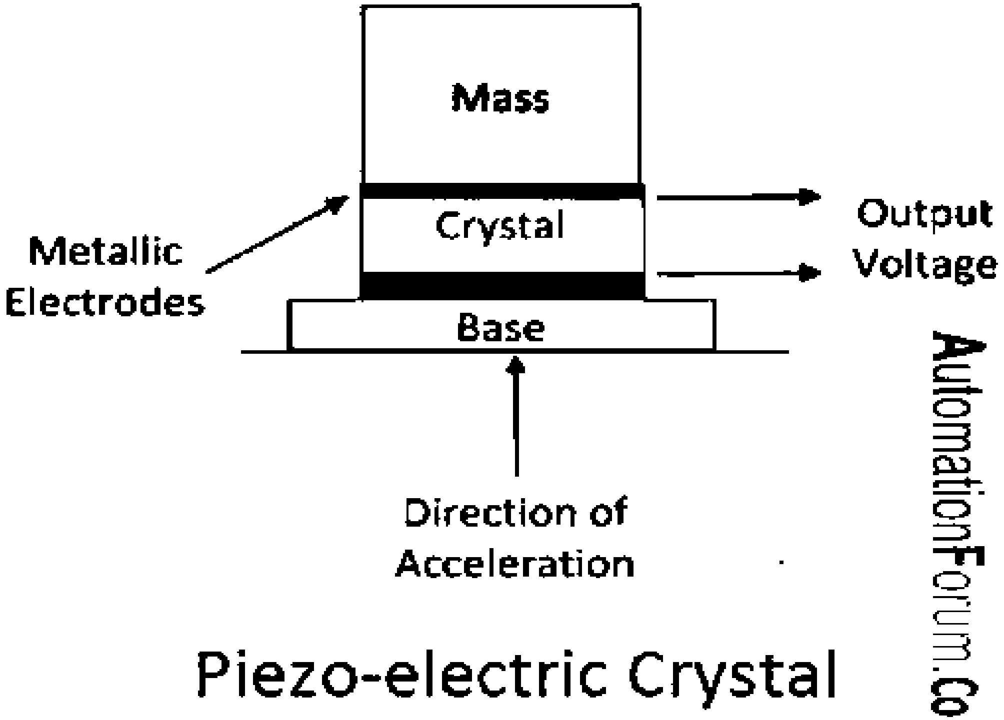
Active transducers are one which develop their output in the form of electrical voltage or current without any auxiliary source. They are also called **self-generating transducers**.

Active transducers draw energy from the system under measurement and such transducers normally give very small output. Thermocouples used for the measurement of temperature, tacho-generators used for the measurement of angular velocity comes under this category.

Eg: Moving coil, Piezoelectric crystal, Thermocouple, Photovoltaic cell

Active

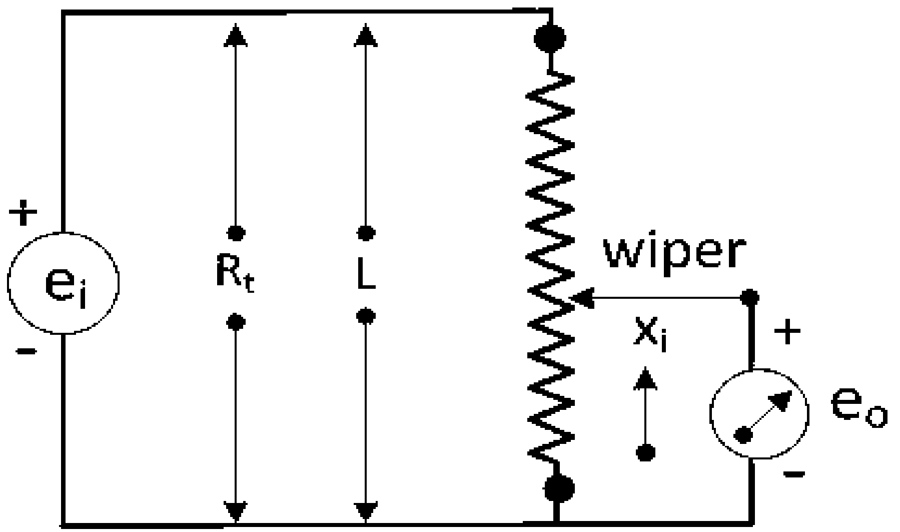




Piezo-electric Crystal

Passive transducers are one which require external power source for energy conversion.

In passive transducers electrical parameters like **resistance, inductance, capacitance** causes a change in voltage, current or frequency of external source. Resistive, inductive and capacitive transducers fall in this category.



Linear Potentiometer (Pot), a passive transducer

Analog and Digital transducer

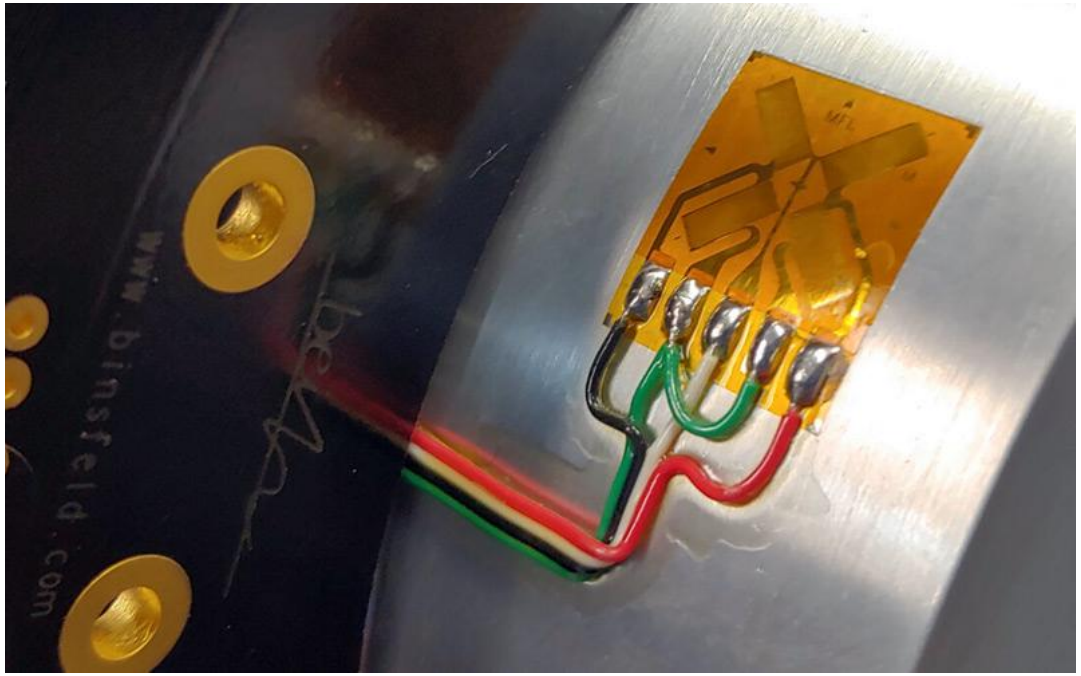
Transducers, on the basis of nature of output can be classified as analog and digital.

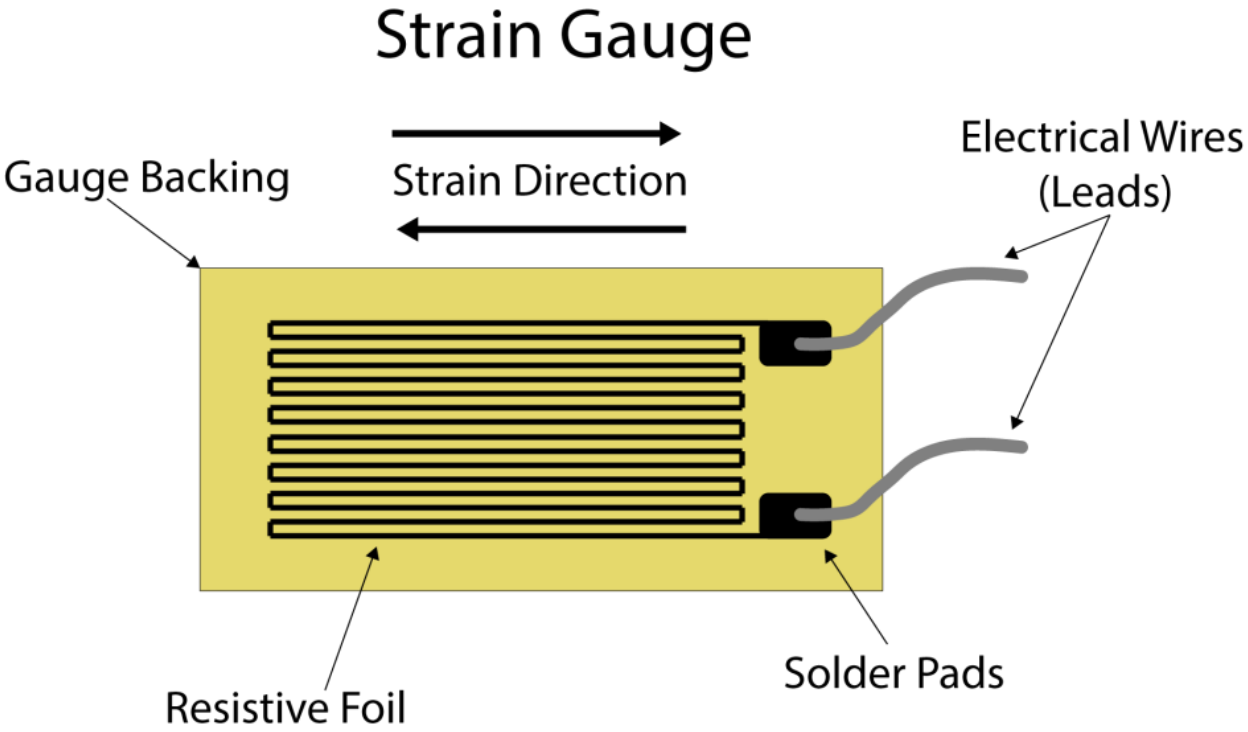
Analog transducers: These type of transducers which convert input signal into output in the form of a continuous function of time such as thermistor, LVDT, thermocouple etc.

Eg: Strain gauge, LVDT, Thermocouple, Thermistor.

Digital transducers: These type of transducers which convert input signal into output in the form of pulses. The examples of digital transducers are linear displacement transducers using conducting and non-conducting contacts, opaque and translucent segments and shaft encoders. It can be easily represented by opaque and transparent areas on a glass scale or non-conducting and conducting areas as the binary system uses only two symbols 0 and 1.

Eg: Glass scale, Metallic scale.




Strain Gauge
Strain Direction
Gauge Backing
Electrical Wires
(Leads)
Resistive Foil
Solder Pads


129.3
lb

Transducers and Inverse transducers

The basic requirement for control of physical quantities such as **position, speed, temperature pressure and flow rate** in an industrial plant is the ability to measure these quantities.

The control action is only possible if the physical quantity can be measured.

Transducers as early mentioned converts a non-electrical quantity into electrical whereas **inverse transducers converts an electrical quantity into some other forms.**

Eg: Peizo electrical crystal

Advantages and Disadvantages of Electrical Transducers

Advantages

1. Electrical signal obtained from electrical transducer can be easily processed (mainly amplified) and brought to a level suitable for output device which may be an indicator or recorder
2. The electrical systems can be controlled with a very small level of power
3. The electrical output can be easily used, transmitted, and processed for the purpose of measurement.
4. With the advent of IC technology, the electronic systems have become extremely small in size, requiring small space for their operation.
5. No moving mechanical parts are involved in the electrical systems. Therefore there is no question of mechanical wear and tear and no possibility of mechanical failure.

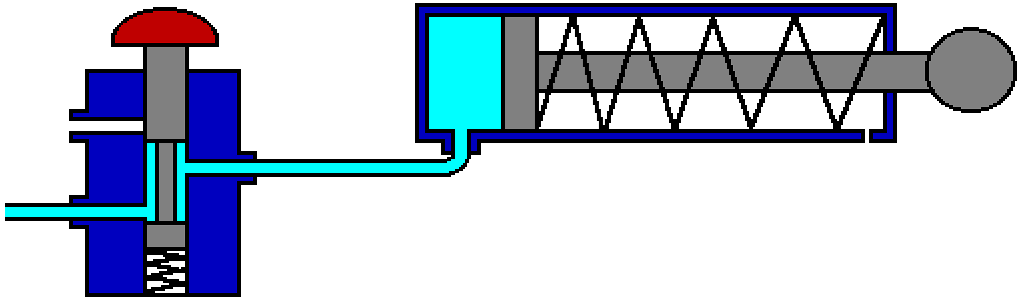
Disadvantages of Electrical Transducer

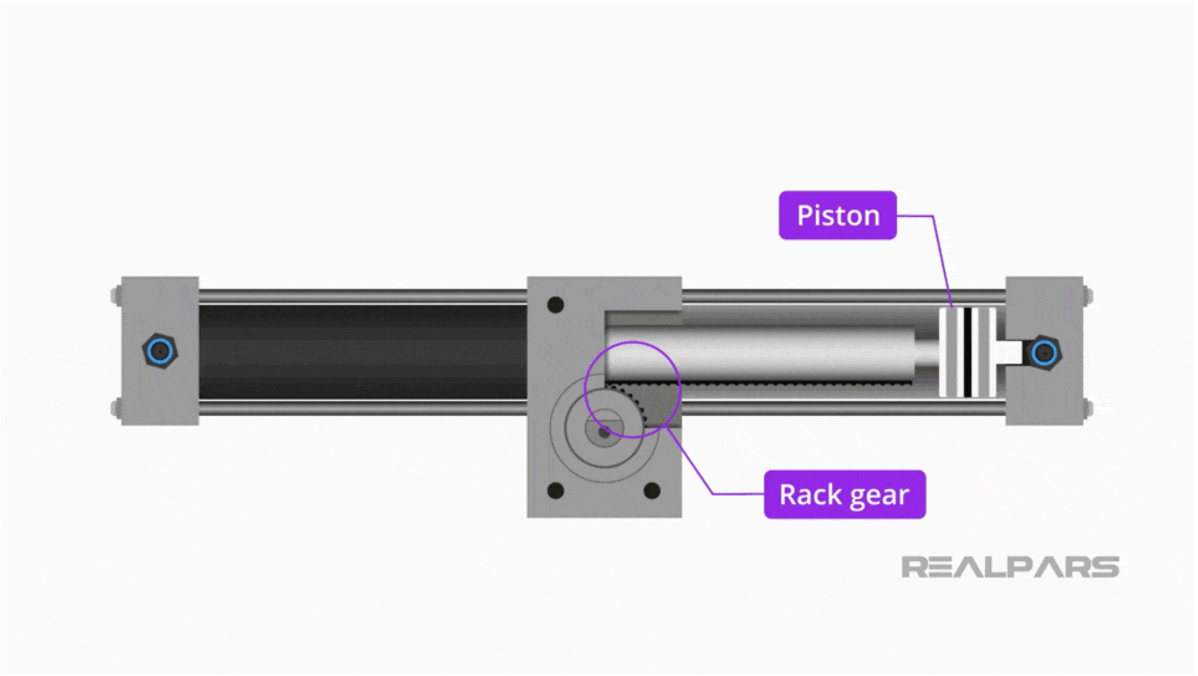
1. The electrical transducer is sometimes less reliable than mechanical type because of the ageing and drift of the active components.
2. Also, the sensing elements and the associated signal processing circuitry are comparatively expensive.
3. With the use of better materials, improved technology and circuitry, the range of accuracy and stability have been increased for electrical transducers.
4. Using negative feedback technique, the accuracy of measurement and the stability of the system are improved, but all at the expense of increased circuit complexity, more space, and obviously, more cost.

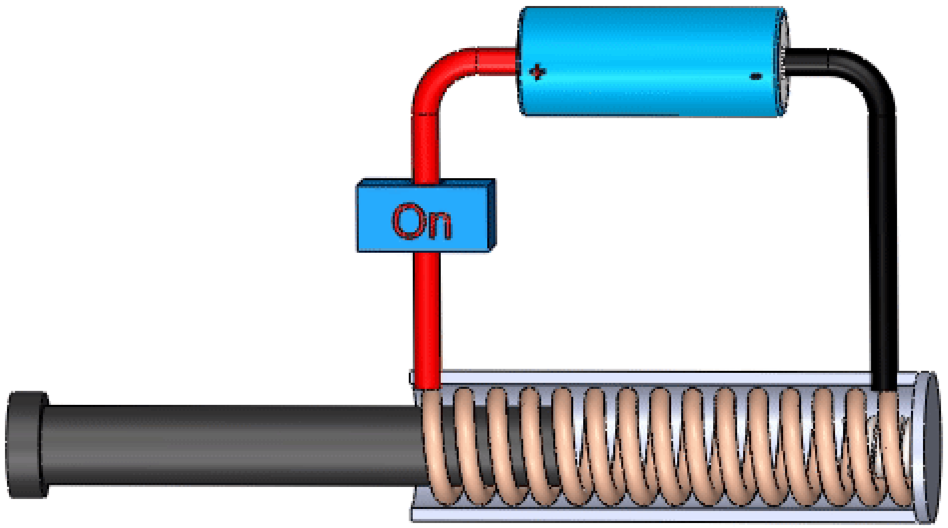
Transducer actuating mechanism

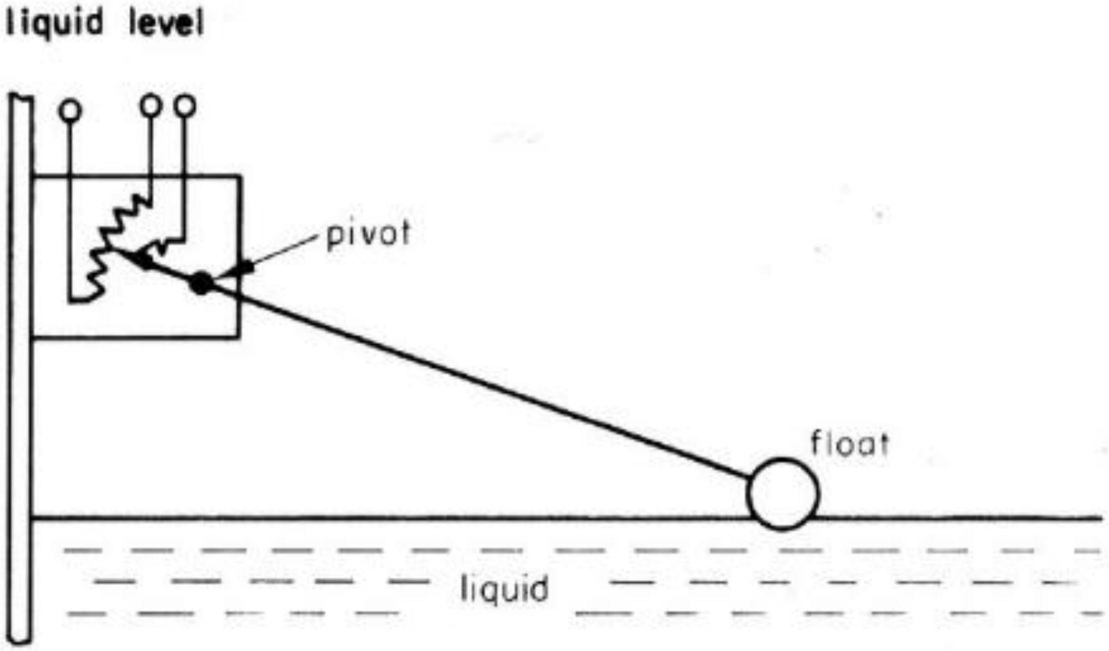
An actuating mechanism usually consists of a **motor**, a **transmission**, and **control units**, as well as **feedback**, **signalling**, **interlocking,** and **shutoff units**.

Actuating mechanisms to control the flow of fluids or gases consist of a valve, shutter, or gate, which is moved by **hydraulic,** **pneumatic**, or **electrical drive**.

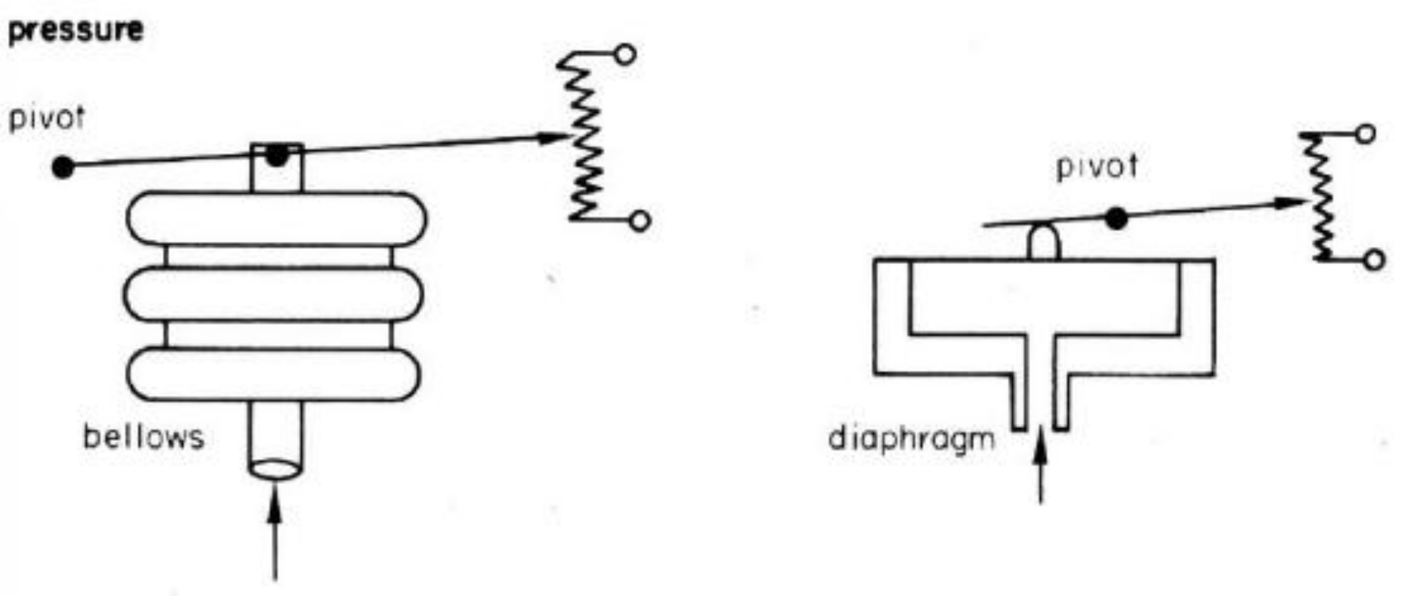



Piston
Rack gear
REALPARS

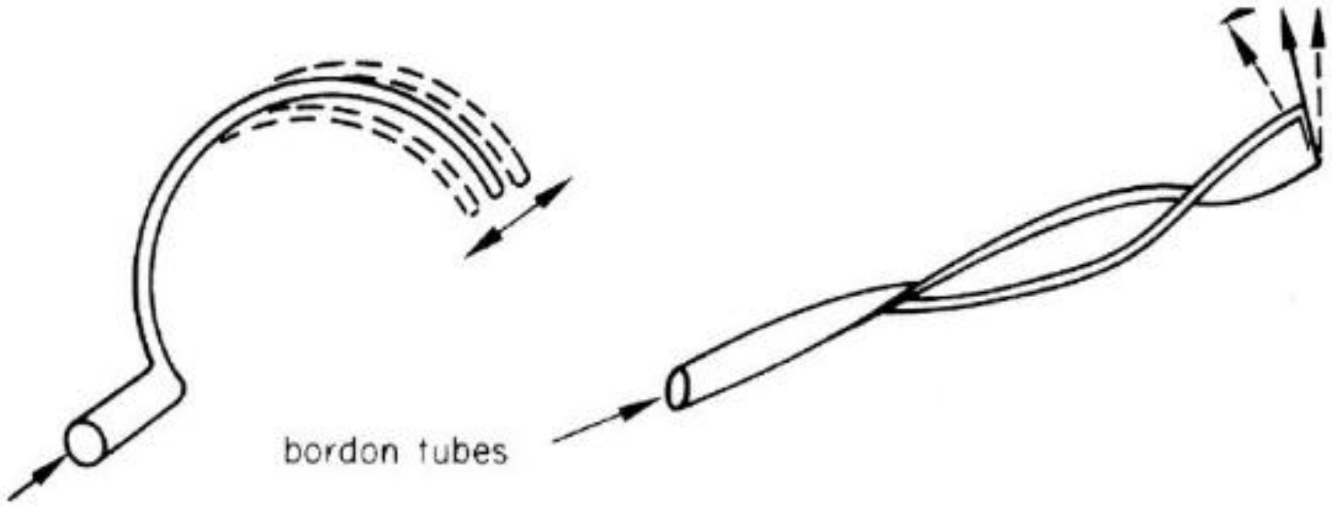

On
+
-



- A Potentiometer used with a float to measure liquid level.
- Is this used in a car to measure petrol?.

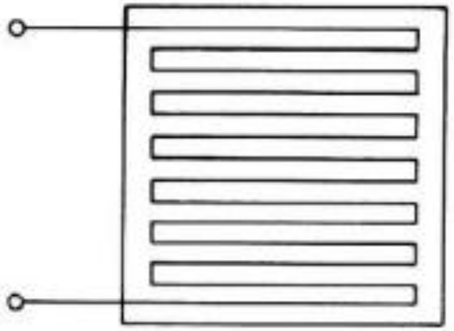


- A Potentiometer used with bellows or a diaphragm to measure presure

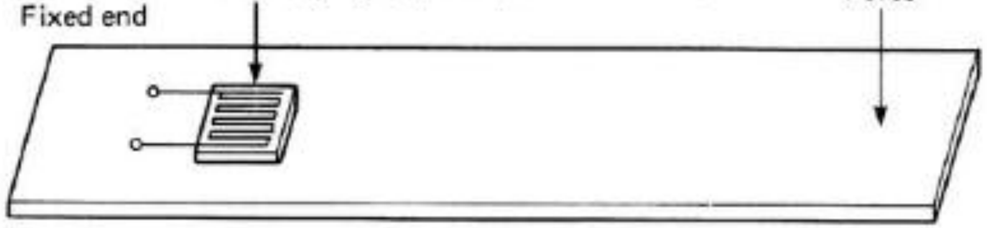


Some transducer actuating mechanisms

- Other ways to measure pressure.

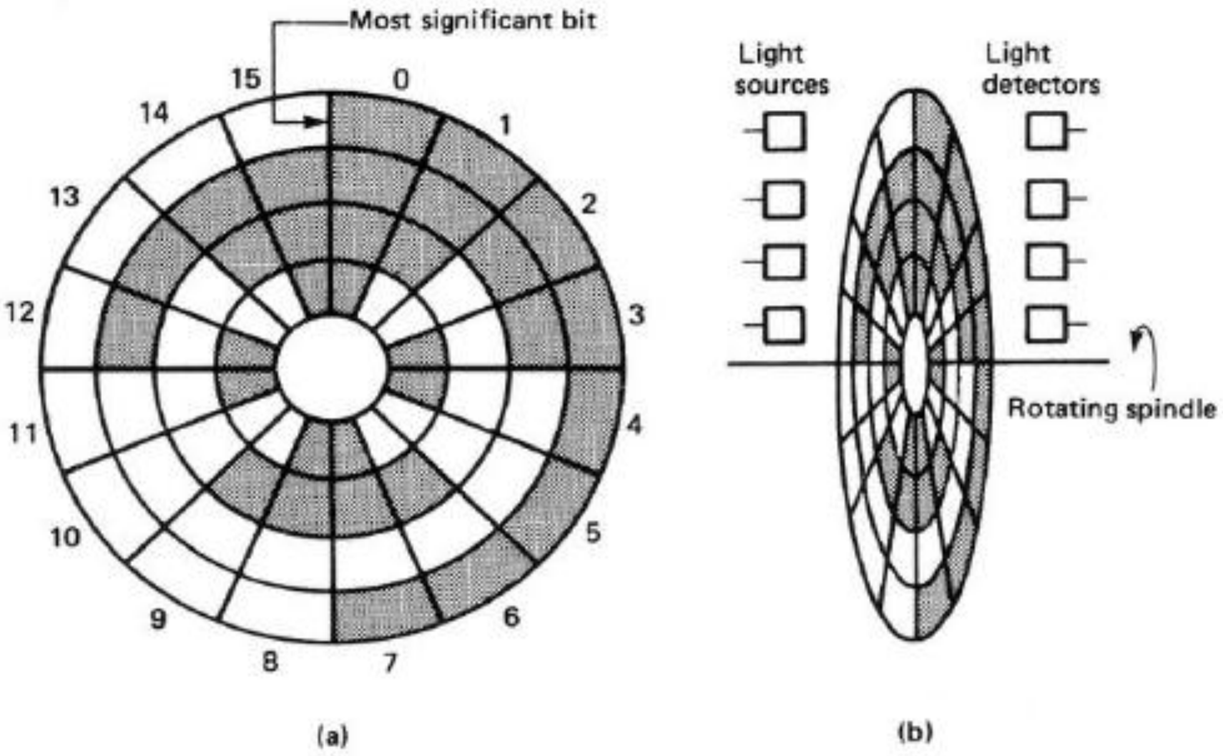


(a)

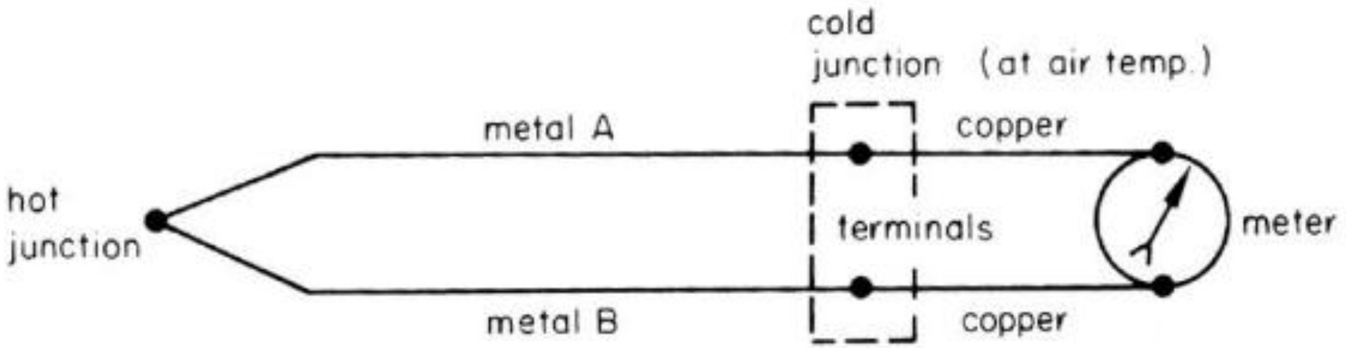


(b)

- A strain gauge can be used to measure force.
- This could be used as a weighing machine.



- Optics can be used to give a digital output directly. In this case rotational position is being measured.



Commonly used thermocouple circuit

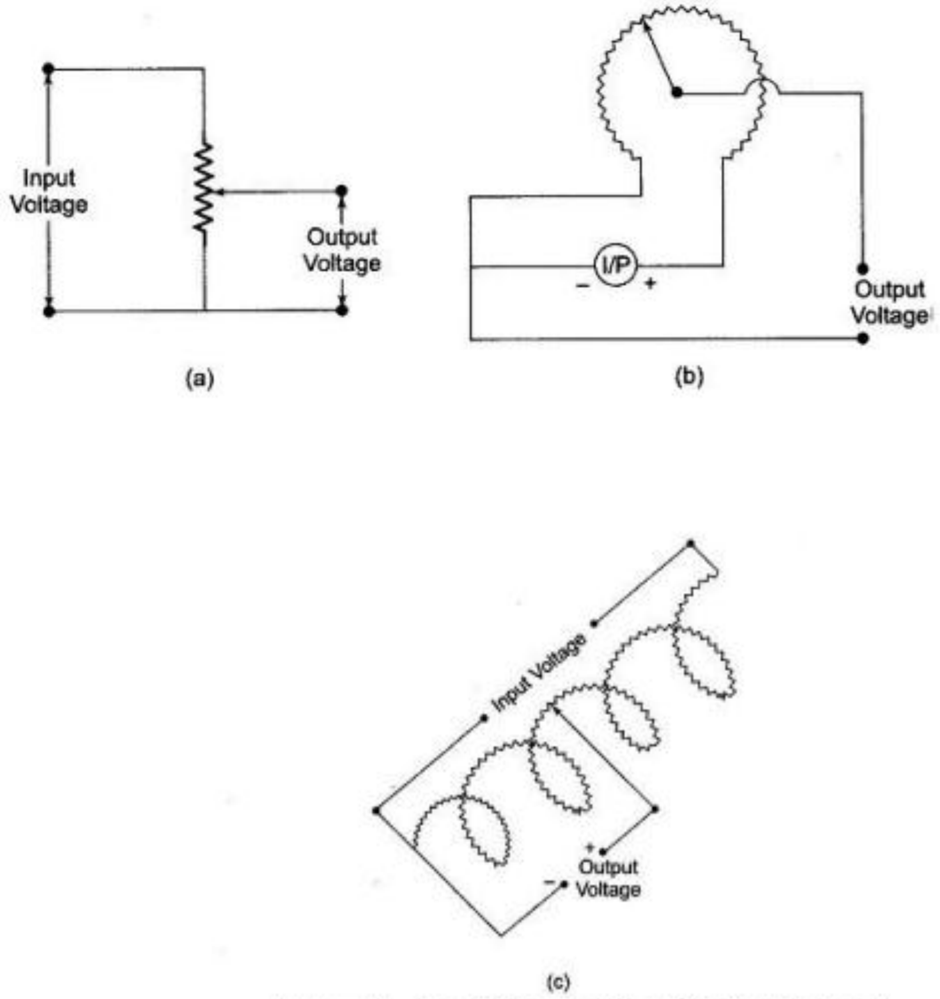
- A thermo couple uses two different metals that generate a voltage when they are heated.

Resistive Transducer

1. Resistive Transducer are those in which the **resistance changes** due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure **displacement.**
2. Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained.
3. This can be used for the measurement of **displacement, force and pressure**. The resistivity of materials changes with changes in temperature. This property can be used for the measurement of temperature.

Potentiometer

1. A resistive potentiometer (pot) consists of a resistance element provided with a **sliding contact**, called a wiper. The motion of the sliding contact may be **translatory or rotational**.
2. Some have a combination of both, with resistive elements in the form of a helix, as shown in Fig. They are known as helipots. Translatory resistive elements, as shown in Fig. a), are linear (straight) devices. Rotational resistive devices are circular and are used for the measurement of angular displacement, as shown in Fig.(b).

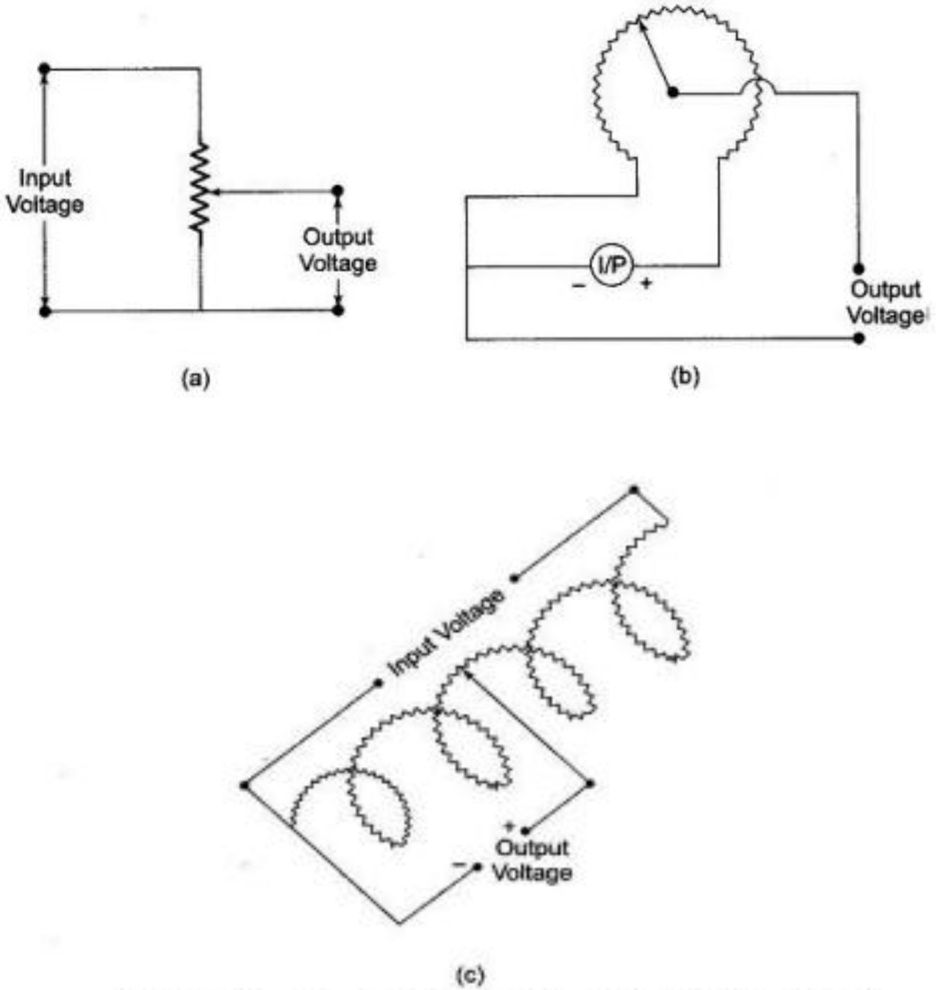


(a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)

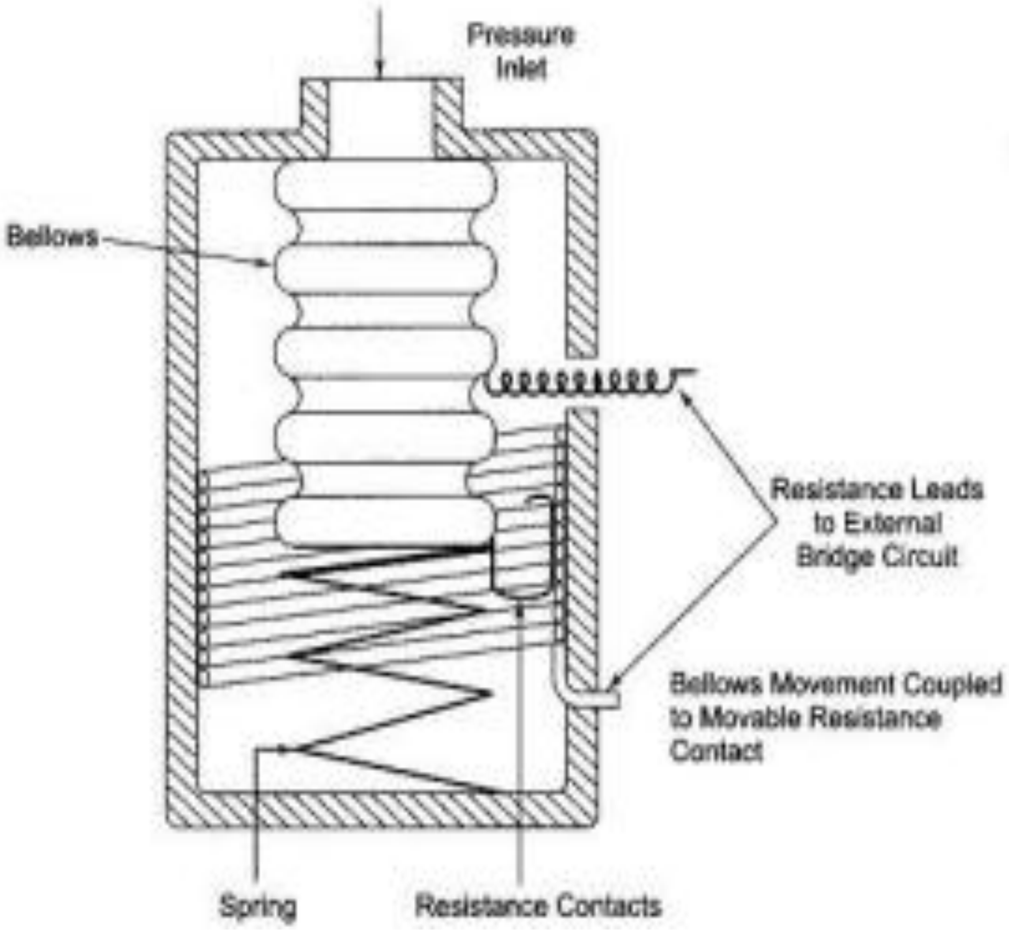
Potentiometer

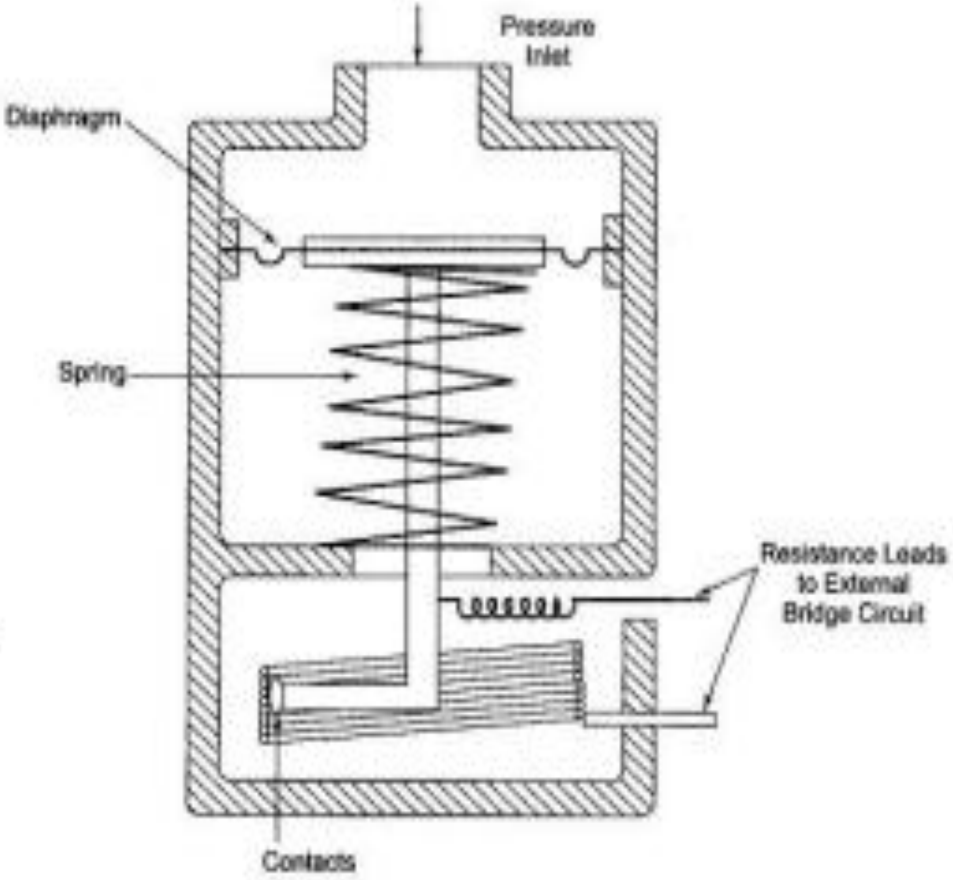
3. **<u>Helical resistive elements</u>** are multi turn rotational devices which can be used for the measurement of either translatory or rotational motion.

4. A potentiometer is a passive transducer since it requires an external power source for its operation.



(a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)


Pressure Inlet
Bellows
Resistance Leads to External Bridge Circuit
Bellows Movement Coupled to Movable Resistance Contact
Spring
Resistance Contacts


Pressure Inlet
Diaphragm
Spring
Resistance Leads to External Bridge Circuit
Contacts

CAPACITIVE PRESSURE SENSORS

Capacitive Transducers

The capacitive transducer is used for measuring the **displacement**, **pressure** and other physical quantities.

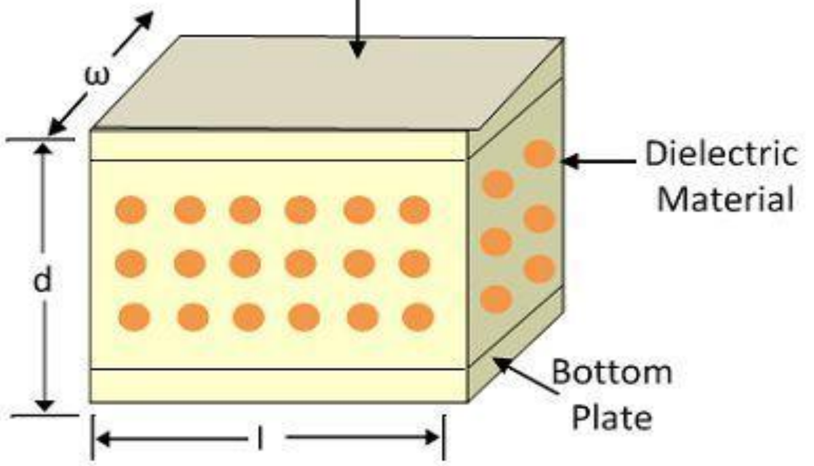
It is a passive transducer that means it requires external power for operation.

The capacitive transducer works on the principle of **variable capacitances**.

The capacitance of the capacitive transducer changes because of many reasons like **overlapping of plates**, **change in distance between the plates** and **dielectric constant**.

Capacitive Transducers

1. The capacitive transducer contains **two parallel metal plates**. These plates are separated by the dielectric medium which is either **air, material, gas or liquid**. In the normal capacitor the distance between the plates are fixed, but in capacitive transducer the **distance between them are varied.**
2. The capacitive transducer uses the electrical quantity of capacitance for converting the **mechanical movement into an electrical signal**. The input quantity causes the change of the capacitance which is directly measured by the capacitive transducer.
3. The capacitors measure both the **static and dynamic changes**. The displacement is also measured directly by connecting the measurable devices to the movable plate of the capacitor. It works on with both the contacting and non-contacting modes



Parallel Plate Capacitive Transducer

$$C = \varepsilon A/d$$

$$C = \varepsilon_r \varepsilon_0 A/d$$

Where A – overlapping area of plates in m^2

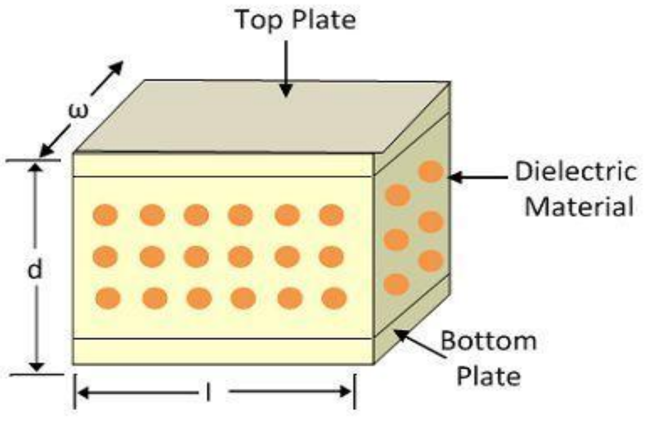
d – the distance between two plates in meter

ε – permittivity of the medium in F/m

ε_r – relative permittivity

ε_0 – the permittivity of free space

The schematic diagram of a parallel plate capacitive transducer is shown in the figure below.



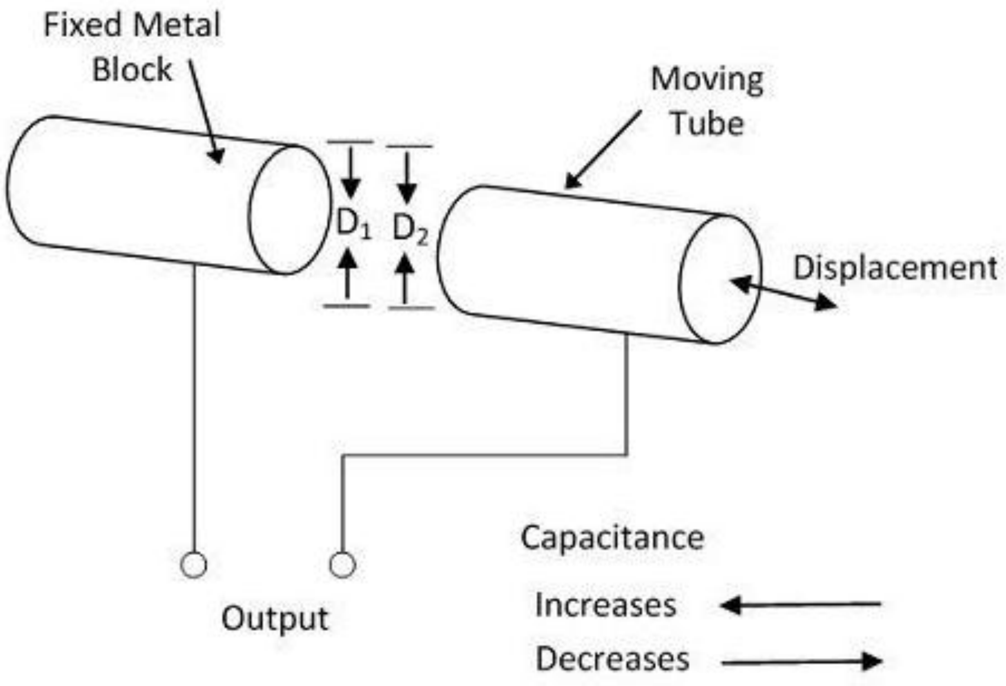
Parallel Plate Capacitive Transducer

The capacitance of the transducer is measured with the bridge circuit. The output impedance of transducer is given as

$$X_c = 1/2\pi f c$$

Where, C – capacitance

f – frequency of excitation in Hz.



Capacitive Transducer

The capacitance of the parallel plates is given as

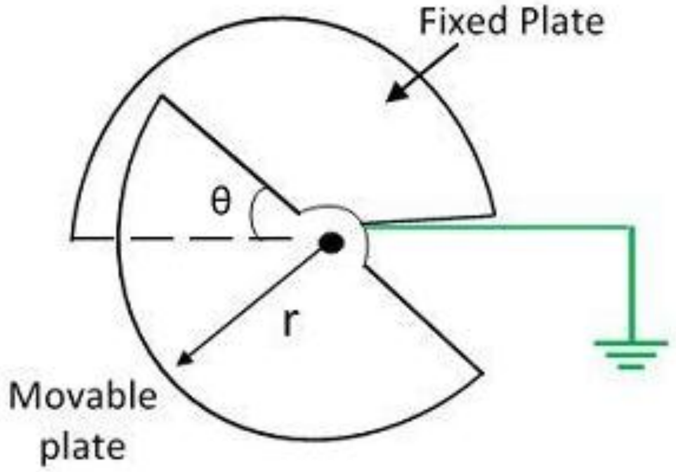
$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon x \omega}{d} F$$

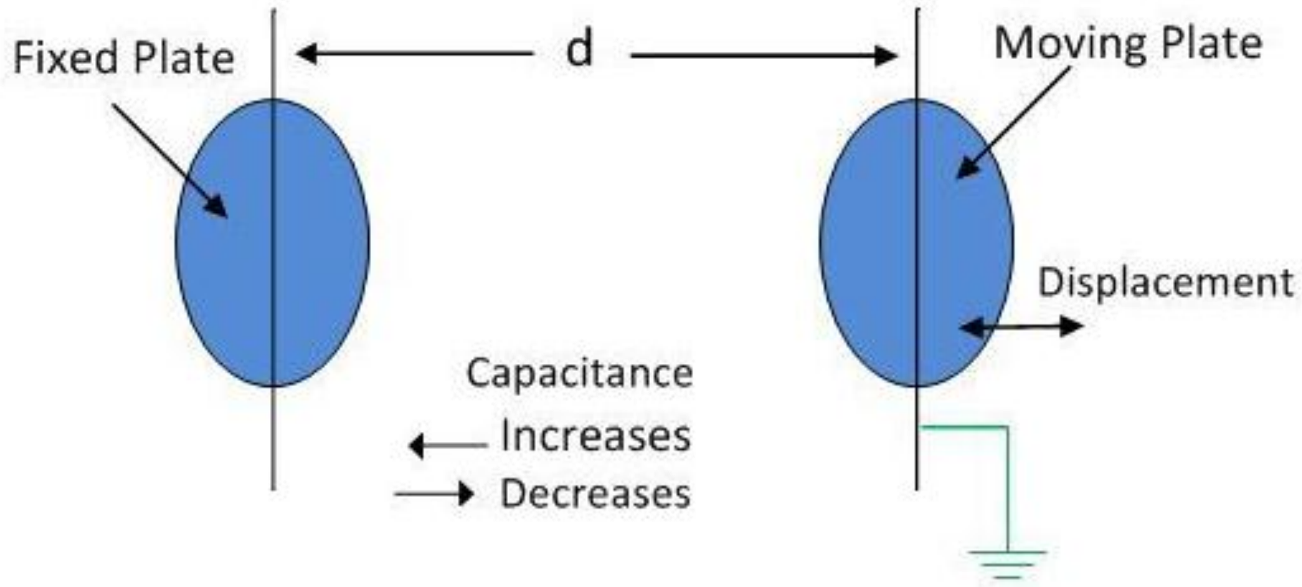
where x – the length of overlapping part of plates

ω – the width of overlapping part of plates.

The sensitivity of the displacement is constant, and therefore it gives the linear relation between the capacitance and displacement.

$$S = \frac{\partial C}{\partial x} = \varepsilon \frac{\omega}{d} F/m$$




Fixed Plate
d
Moving Plate
Displacement
Capacitance
Increases
Decreases

CAPACITIVE PRESSURE SENSORS

Among the pressure sensors that are widely used in the industry, capacitive pressure sensors are particularly noteworthy.

These sensors are characterized by

- **Very low temperature hysteresis** and
- **Pressure hysteresis**
- **Low power consumption**

Traditional capacitive pressure sensors, however, suffer from inherently **poor resolution**

New capacitive pressure sensors with extremely high resolution and sensitivity, based on nanotechnology

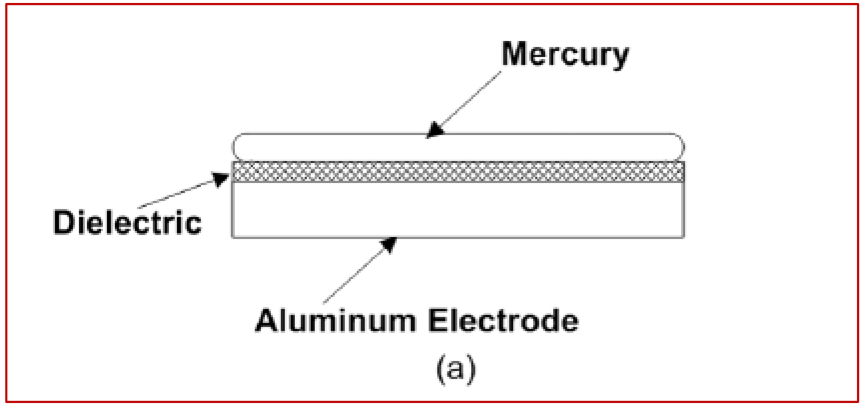
Structure

- The recently introduced **mercury-droplet capacitive pressure sensor** has demonstrated a change in capacitance of approximately 6.73 µF over a pressure range of 0 to 3 kPa.

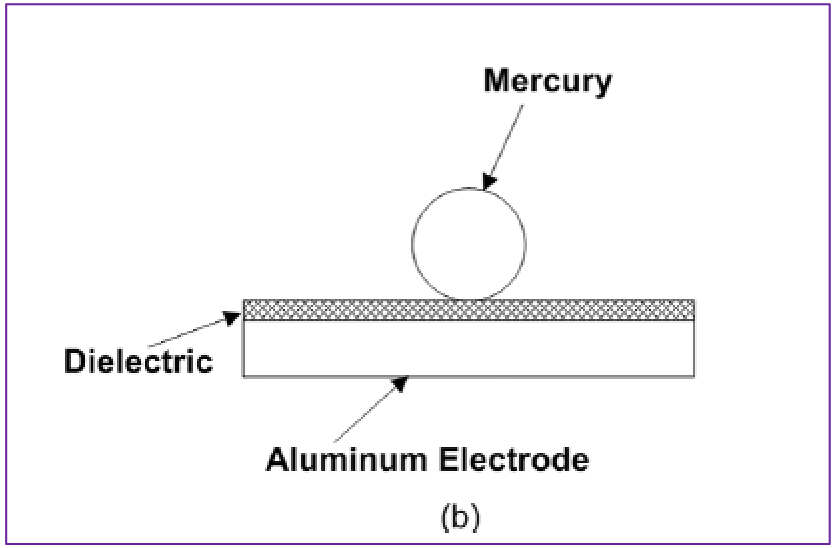
- The sensitivity of this type of sensor is therefore **2.24 µF/kPa**, substantially higher than any of the known types of capacitive pressure sensors.
- The basic concept of the new sensor is to **mechanically deform a drop of mercury** that is separated from a flat aluminum electrode by a very thin layer of a dielectric material, so as to form a **parallel-plate capacitor** where the electrode area is variable to a high degree.
- This principle is illustrated in Figure 1.1
- The principle of the new device, therefore, is to create a capacitor with a variable electrode area, rather than a variable inter electrode spacing

(a)A drop of mercury is flattened against an aluminum electrode that is covered with a layer of a **dielectric material.**

A parallel-plate capacitor with one liquid electrode is formed.



(b) **Under zero pressure**, the mercury drop returns to its nearly spherical shape. The change in capacitance between the two configurations (which is proportional to the change in the contact area of the liquid electrode) can be several hundred fold



The drawback, however, is that the **maximum temperature-related error** is slightly worse than that of the other capacitive pressure sensors (due to the thermal expansion of the mercury droplet, particularly at high temperatures)

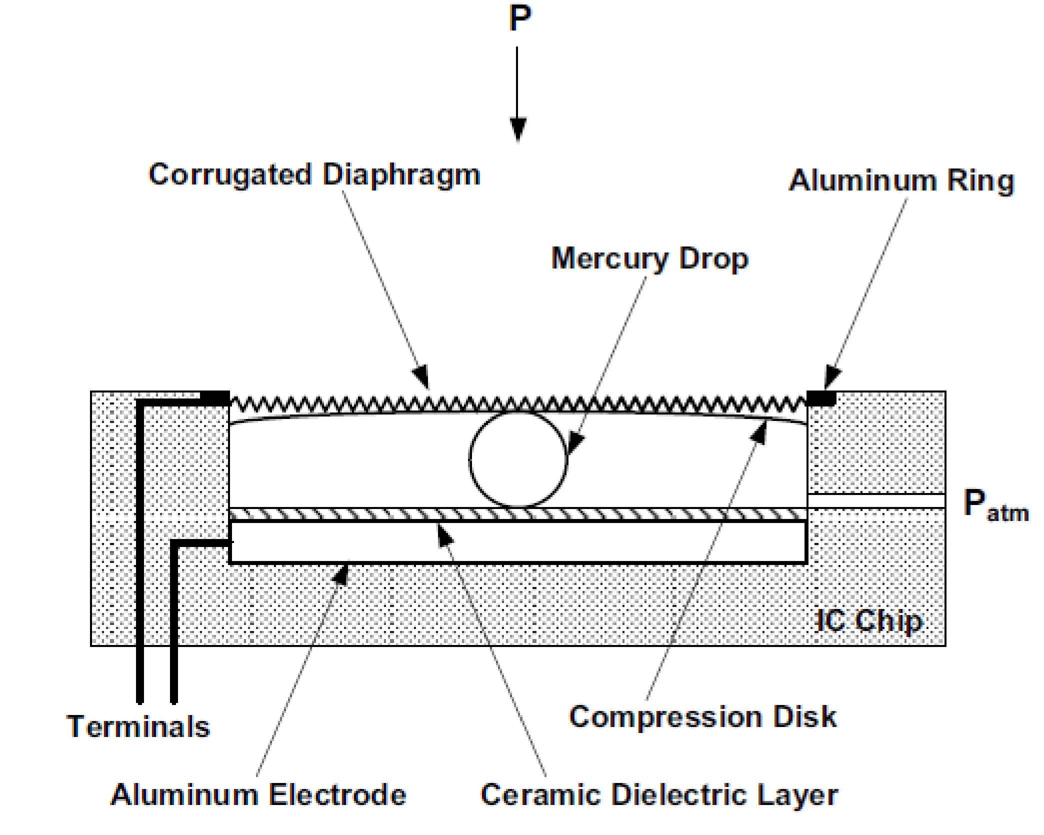
	Sensitivity	Linearity	Pressure Hysteresis	Temperature Hysteresis (For temp. range of −10°C to +80°C)
Piezoresistive pressure sensors	Up to 25 mv/kPa	Generally linear	Up to ± 1% FSO	Up to ± 2% FSO
Capacitive pressure sensors	Up to 0.2 nF/kPa	Generally nonlinear	Up to ± 0.1% FSO	Up to ± 0.5% FSO
New sensor (uncompensated)	2.24 μF/kPa	Nonlinear	Less than ± 0.05% FSO	Up to ± 1.5% FSO

Mechanical structure of the sensor

Step-1:A drop of mercury of a 3 mm diameter is placed on top of a flat aluminum electrode that is covered with a 1 μm thick layer of a ceramic material that has a very high dielectric constant

Step-2: The drop is held in place by means of an aluminum disk that serves as the compression mechanism

Step-3: The compression disk, in turn, is acted upon by means of a corrugated stainless steel diaphragm,

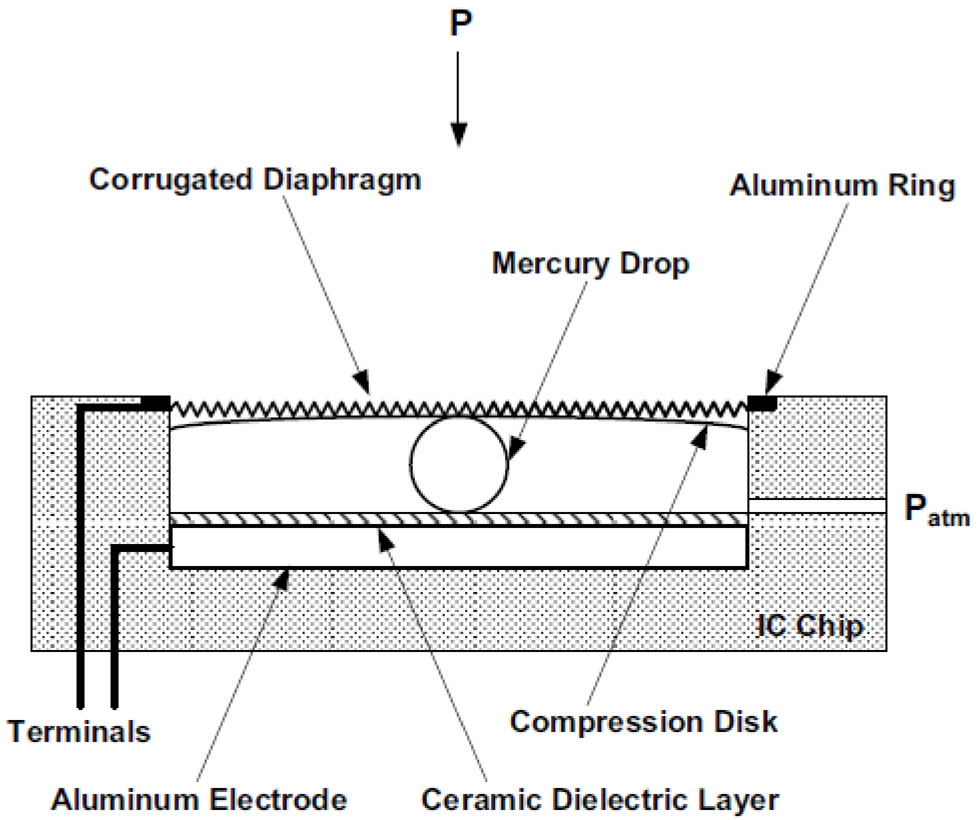


Mechanical structure of the sensor

Step-4: The compression disk is given a slight curvature, as shown in the figure, such that the spacing between the disk and the ceramic layer is exactly 3 mm at the center, but less than 3 mm everywhere else. In this manner, the mercury drop will be forced to the center each time the stainless steel diaphragm retracts.

Step-5: The diaphragm is held in place by means of a thin aluminum ring

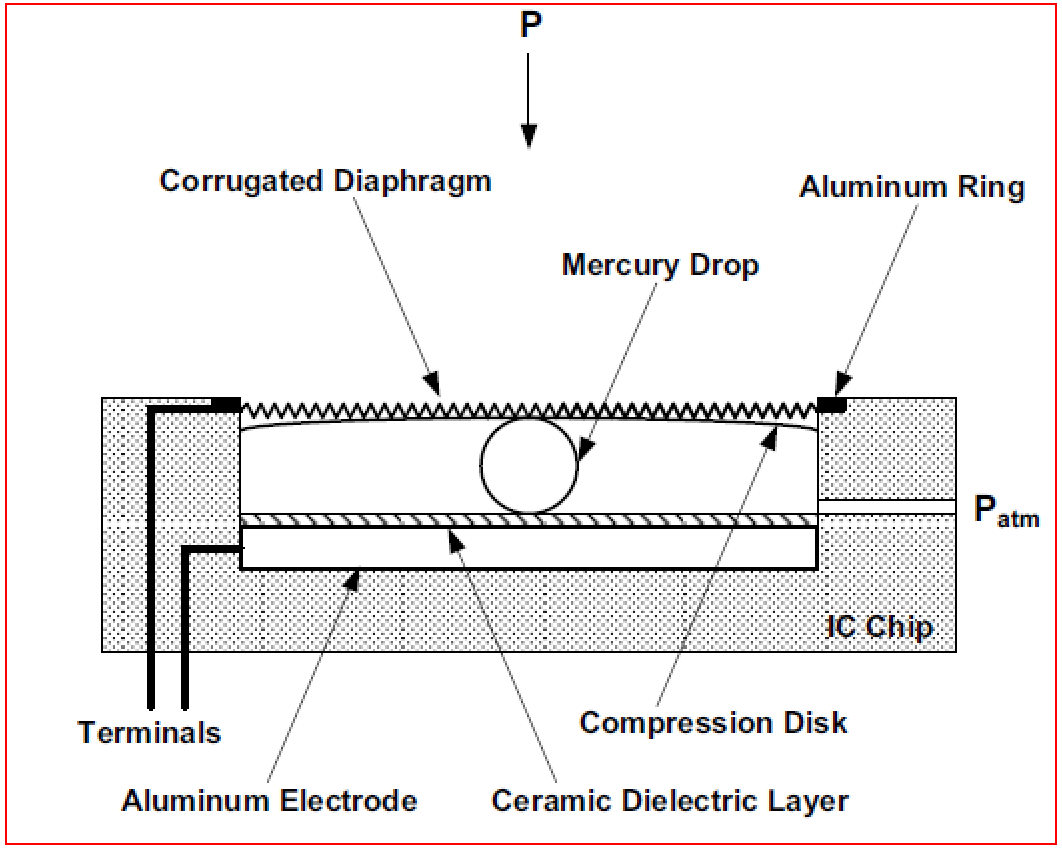
Step-6: The entire assembly is mounted inside an open-cavity, 24-pin DIP IC package.



Mechanical structure of the sensor

Step-7: Since the air that surrounds the mercury droplet must be allowed to exit from the sensor and re-enter as the sensor is pressurized/depressurized, an atmospheric pressure relief conduit is drilled in the IC package,

In **applications** where it is desired to detect pressures that are lower than the atmospheric pressure at sea level (like aircraft altitude applications, for example), then a suitable vacuum can be initially applied to the pressure relief conduit

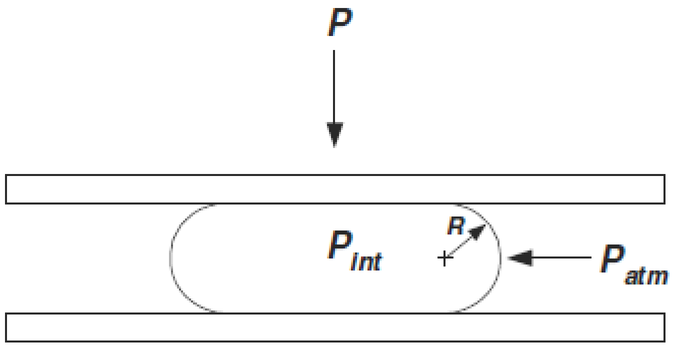


Theory

Step-1: Figure shows the geometry of a drop of mercury that is deformed between two solid surfaces.

Step-2: The vertical pressure that is acting on the drop is P, and the lateral pressure is the atmospheric pressure P_{atm}.

Step-3: P_{int} is the internal pressure, and R is the radius of curvature of the part of the surface of the liquid that is not flattened



Pressures and geometry in the deformation of a drop of mercury

Step-4: The internal pressure P_{int} in the liquid must be balanced by the atmospheric pressure plus the **Laplace pressure, or the pressure due to surface tension**

$$P_{int} = P_{atm} + \frac{2\gamma}{R}$$

where 2Y /*R* is the Laplace pressure and g is the surface tension of mercury

Step-5: As the drop of mercury is flattened, the difference in the internal pressure will be equal to the applied pressure *P*,

$$P = P_{int} - (P_{int})_0$$

where $(P_{int})_0$ is the internal pressure at zero applied pressure

By using Eq. (1.1), Eq. (1.2) can be written as follows:

$$P = P_{atm} + \frac{2\gamma}{R} - \left(P_{atm} + \frac{2\gamma}{R_0}\right)$$

where R_0 is the original unflattened radius of the drop

$$P = 2\gamma\left(\frac{1}{R} - \frac{1}{R_0}\right)$$

The capacitance of a parallel plate capacitor is

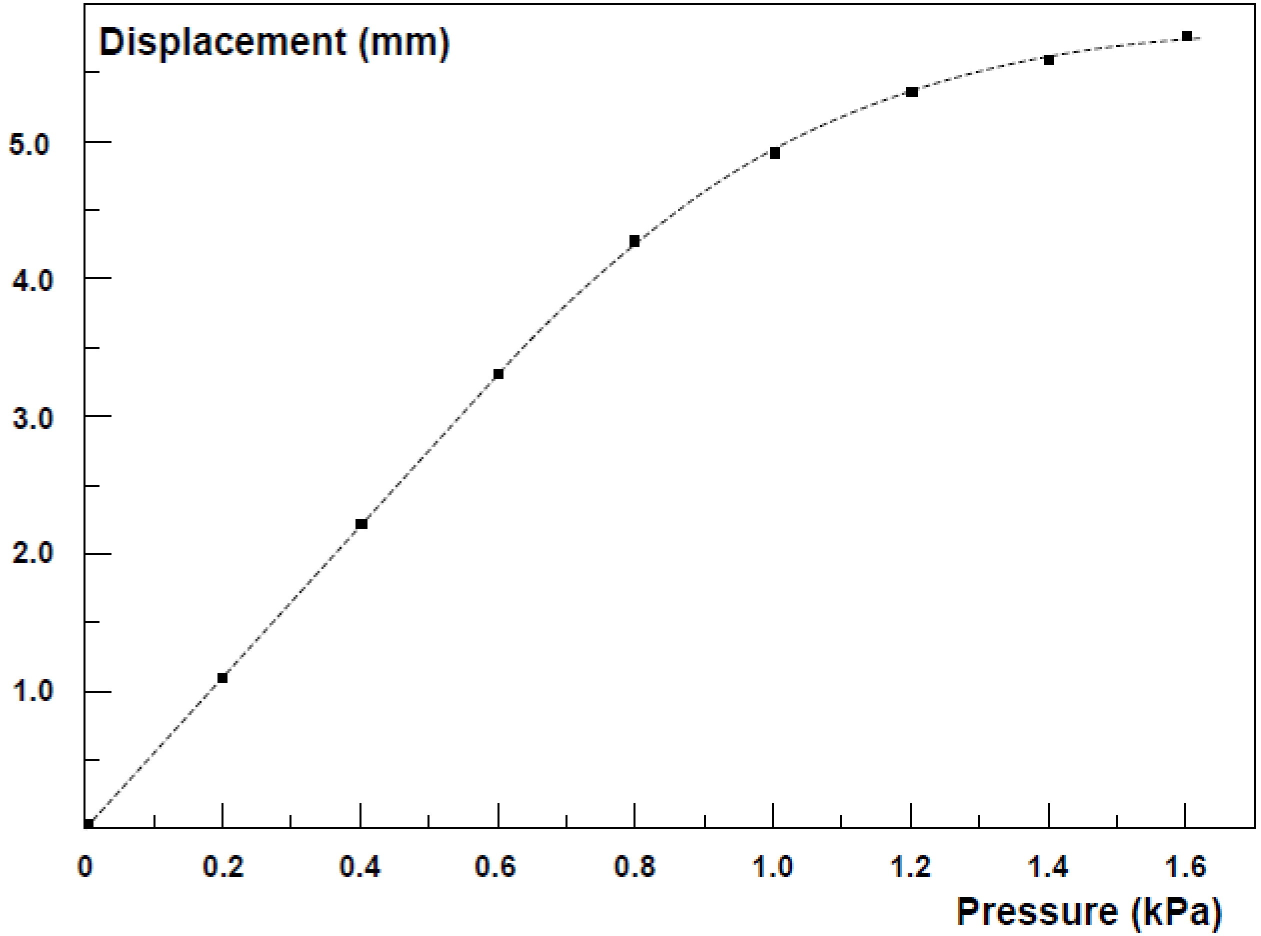
$$\boxed{C = \frac{\varepsilon A}{d}}$$

where e is the permittivity of the dielectric medium,
A is the surface area of the
electrodes, and *d* is the thickness of the dielectric

Calculating the wetting area of the deformed droplet is a simple but rather lengthy and uninformative exercise

$$A = \pi \left[\sqrt{\frac{\pi^2 R^2}{16} + \frac{2R_0^3}{3R}} - \frac{\pi}{4} R \right]^2$$

where R is the radius of curvature of the part of the surface of the liquid that is not flattened


Displacement (mm)
5.0
4.0
3.0
2.0
1.0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Pressure (kPa)

the relationship between the applied pressure and the capacitance can be easily determined as well. That relationship can be represented as

$$P_{dia} = \alpha C$$

where P_{dia} is the pressure acting on the diaphragm and a is the constant of proportionality.

The physical, or total, pressure acting on the sensor is equal to the sum of the two pressures

$$P_{total} = \alpha C - \frac{2\gamma}{R_0} + 2\gamma / \left(\sqrt{\frac{Cd}{\varepsilon\pi^3} + \frac{4}{3}R_0^3\left(\frac{\varepsilon}{\pi C d}\right)^{1/2}} - \sqrt{\frac{Cd}{\varepsilon\pi^3}} \right)$$

Temperature related errors

For large changes in temperature, the error in the calculated pressure for the present sensor is actually slightly higher than other known types of capacitive pressure sensors due to the thermal expansion of the drop of mercury

$$\boxed{L = L_0 \left(1 + \lambda \Delta T\right)}$$

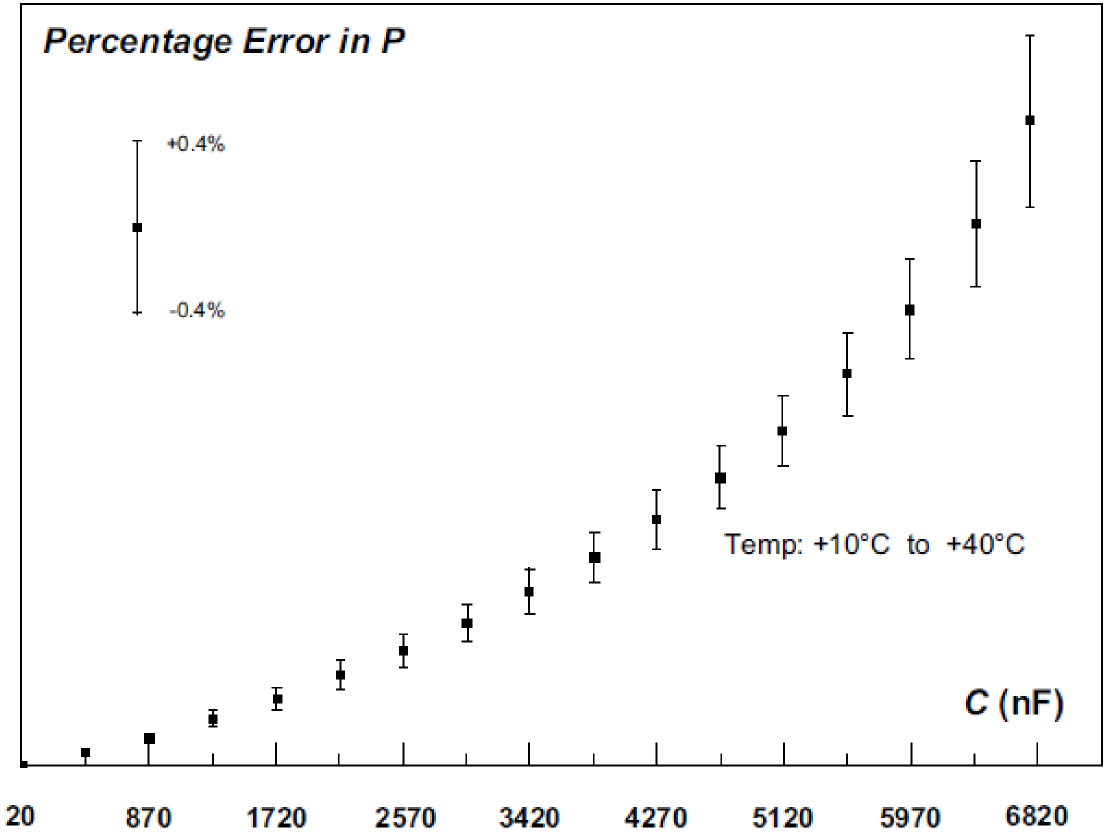
where L is any linear dimension, λ is the metal's expansion coefficient, and ΔT is the change in temperature.

Pressure hysteresis:

The hysteresis in the values of the calculated pressure is determined by **cycling the pressure at a fixed temperature** and plotting the measured pressure versus the actual applied pressure.

Susceptibility to mechanical shocks:

If the sensor is shocked, the mercury drop will be **momentarily displaced** (especially if a small pressure is acting on the drop), and it was observed that a "recovery time" is needed for the drop to return to its original position (and hence for the momentary error to disappear).



Environmental effects:

At elevated temperatures (a few hundred ◦C), mercury reacts with the oxygen in the air to form mercury oxide.

The presence of **mercury oxide can severely degrade the performance of the sensor**.

Generally, the use of this sensor at temperatures above +80◦C is not recommended.

Inductive Pressure Sensors

Pressure sensors exist in mainly two varieties: **piezoresistive and capacitive**.

Piezoresistive pressure sensors are characterized by **good linearity** and **acceptable sensitivity**, but the temperature hysteresis in these sensors is usually quite large

The sensor is characterized by

(1)miniature size (the sensor fits inside an IC package);

(2) Excellent linearity over an arbitrarily chosen pressure range;

(3) substantially high sensitivity;

(4) substantially low temperature hysteresis.

Structure

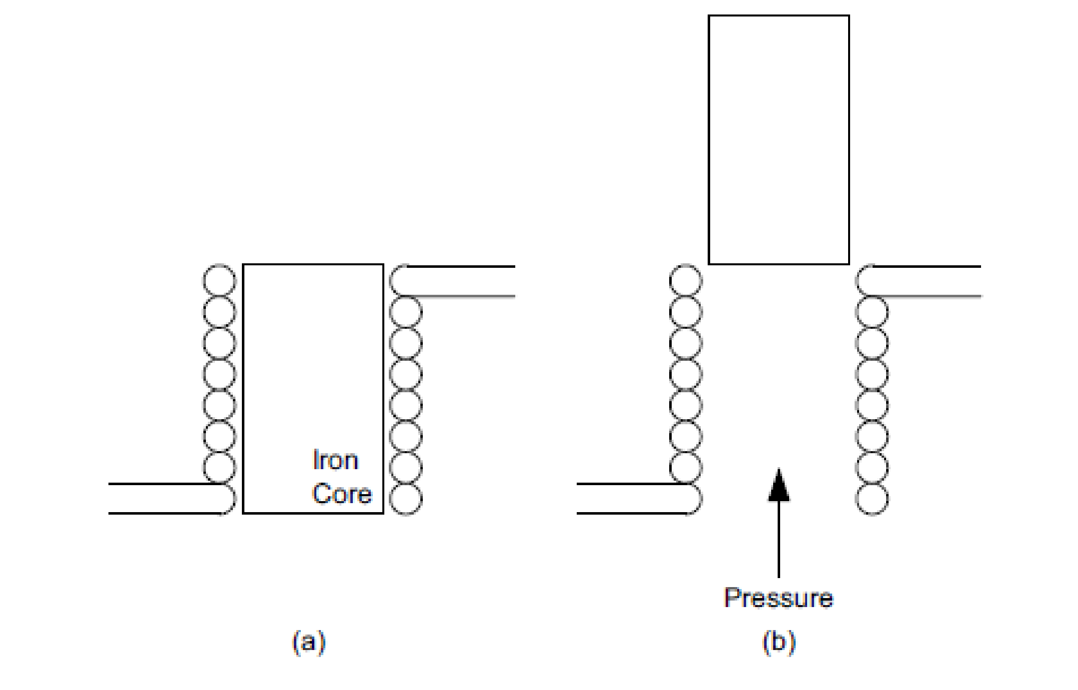
The principle of the new device

Step-1: The change in inductance is equal to the **relative magnetic permeability** of the core material

Step-2: (a) A movable iron core is positioned inside the core of a vertical inductor (coil).

Step-3: (b) As pressure acts on the iron core in the **vertical direction**, the core can be totally displaced outside the coil.

Step-4: The change in inductance between the two configurations is equal to the **relative magnetic permeability of the core material** and is typically 4000-fold or higher.

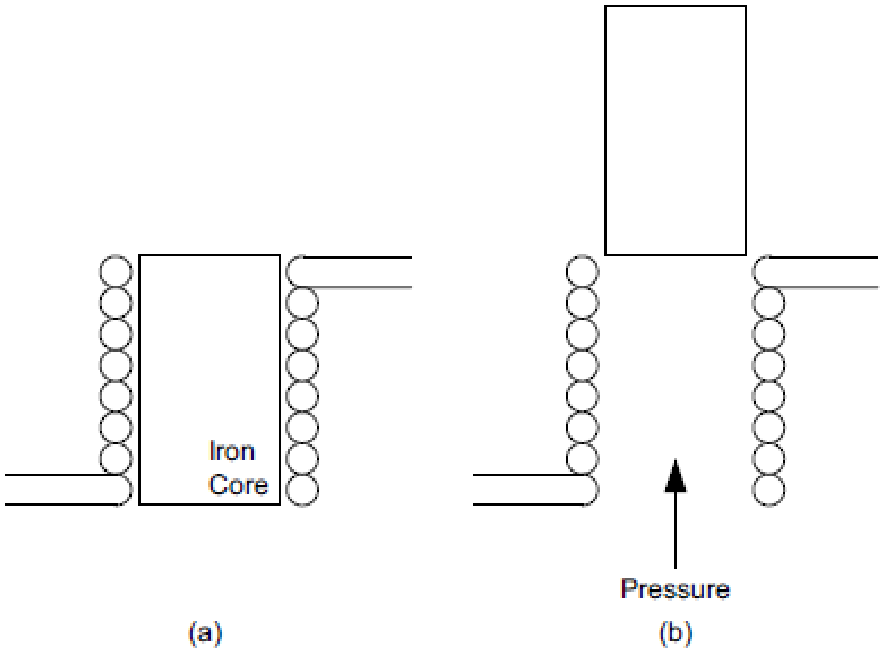


Structure

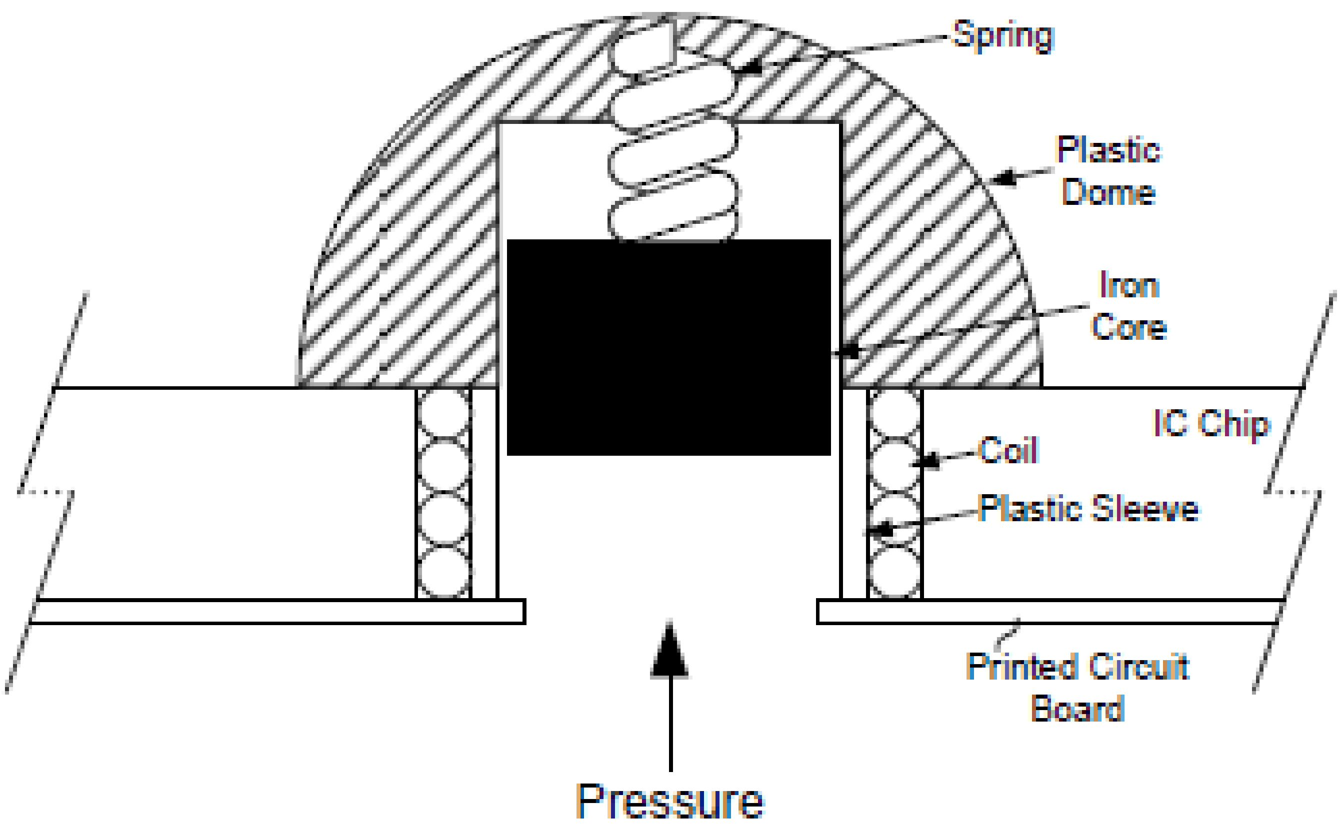
The principle of the new device

Step-5: By comparison with the LVDT, this sensor offers substantially higher sensitivity, does not require AC excitation

A change in inductance of approximately 34.5 mH over a pressure range of 0.3 to 10 kPa.



Structure

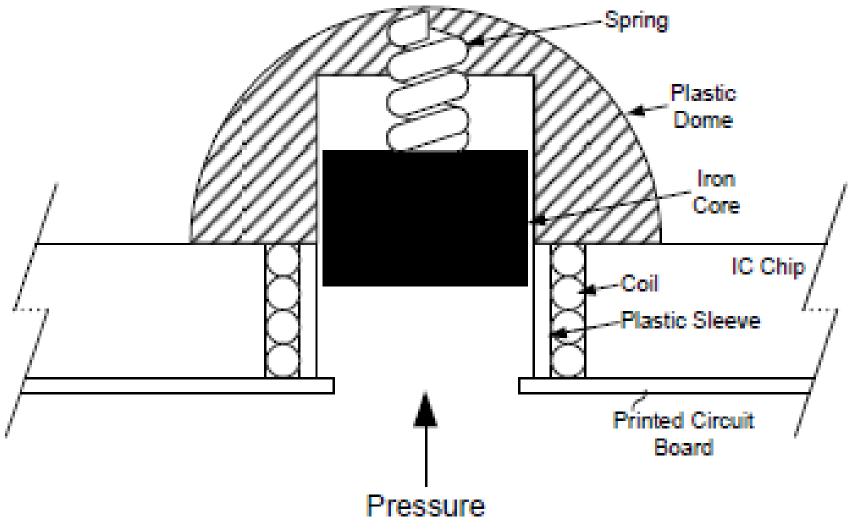

Spring
Plastic Dome
Iron Core
IC Chip
Coil
Plastic Sleeve
Printed Circuit Board
Pressure

Mechanical structure of the sensor

Step-1: A vertical coil of a height of 4 mm and a diameter of 12 mm is totally embedded inside an open-cavity, 24-pin DIP IC package

Step-2: A small cylindrical iron core of a height of 4 mm and a diameter of 6 mm is positioned inside the coil, surrounded by a smooth Teflon sleeve

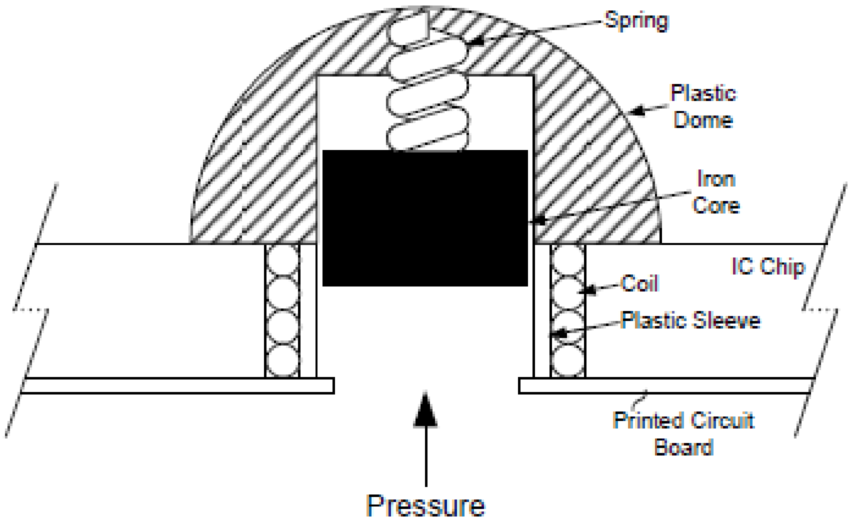
Step-3: In the device shown, the pressure acts on the iron core in the upward direction.



Mechanical structure of the sensor

Step-4: Semi-spherical plastic dome is positioned on top of the coil in order to contain the iron core it displaced

Step-5: In the internal cavity of the dome, a spring with a known spring constant is mounted.



Step-6: As the displaced iron core exerts force on the spring, the displacement will be proportional to the force (and hence pressure) that is acting on the iron core.

Step-7: The displacement of the iron core, in addition, will be related to the observed inductance of the coil.

Theory

Inductance as a function of the position of the iron core:

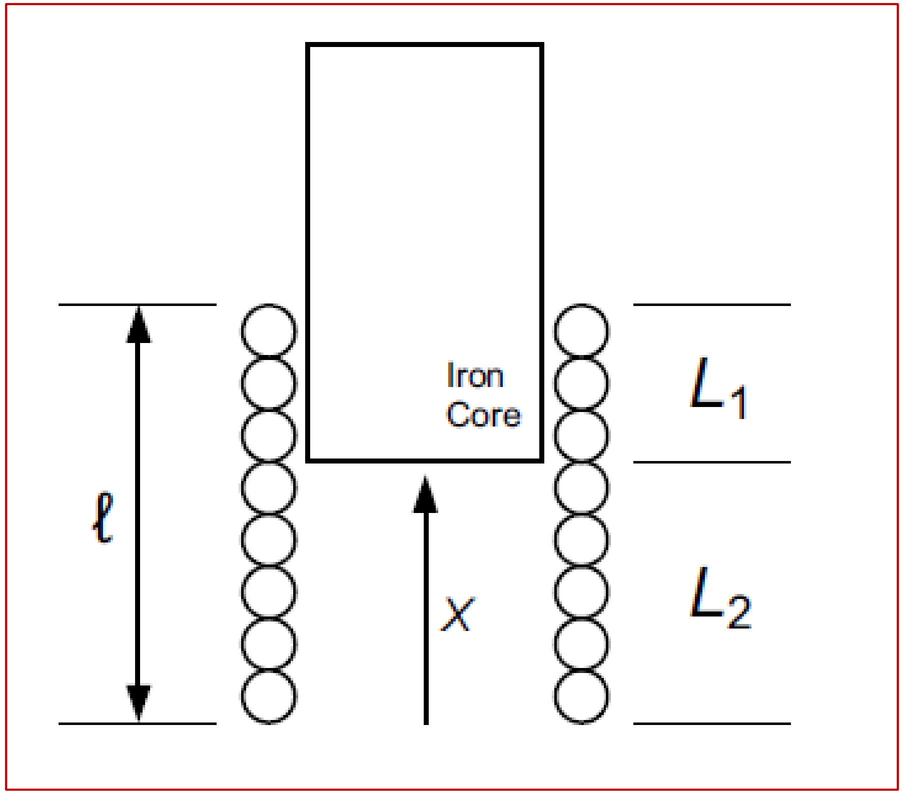
The inductance L of any inductor is given by the well-known equation

$$L = \frac{\mu_0 \mu_r N^2 A}{l}$$

where μ_0 is the magnetic permeability of free space,
μ_r is the relative permeability of the material present in the core,
N is the number of turns in the coil,
A is the cross sectional
area of the coil, and l is its length.

Step-1: Figure shows the creation of two inductors in series as the iron core is displaced by a small distance *x* from its original position.

Step-2: The first inductor contains the iron core and its inductance is labeled L_1,
and the second inductor contains only air in its core and its inductance is labeled L_2.



the inductances L_1 and L_2 will be now given in terms of the displacement x as follows:

$$L_1 = \frac{\mu_0 \mu_r N_1^2 A}{(l-x)}$$

$$L_2 = \frac{\mu_0 N_2^2 A}{x}$$

where N_1 is the number of turns in the first inductor and N_2 is the number of turns in the second inductor

The following two relationships now hold

$$N_1 + N_2 = N$$

$$\frac{N_2}{N} = \frac{x}{l}$$

These two relationships can be alternatively written as follows:

$$\boxed{\begin{aligned} N_1 &= N\left(1-\frac{x}{l}\right) \\ N_2 &= N\left(\frac{x}{l}\right) \end{aligned}}$$

By substitution for N_1 and N_2 from the above two identities

$$\boxed{L_1 = \frac{\mu_0\mu_r N^2 A}{l}\left(1-\frac{x}{l}\right)} \qquad \boxed{L_2 = \frac{\mu_0 N^2 A x}{l^2}}$$

total inductance of a series combination of two inductors is equal to the sum of the individual inductances

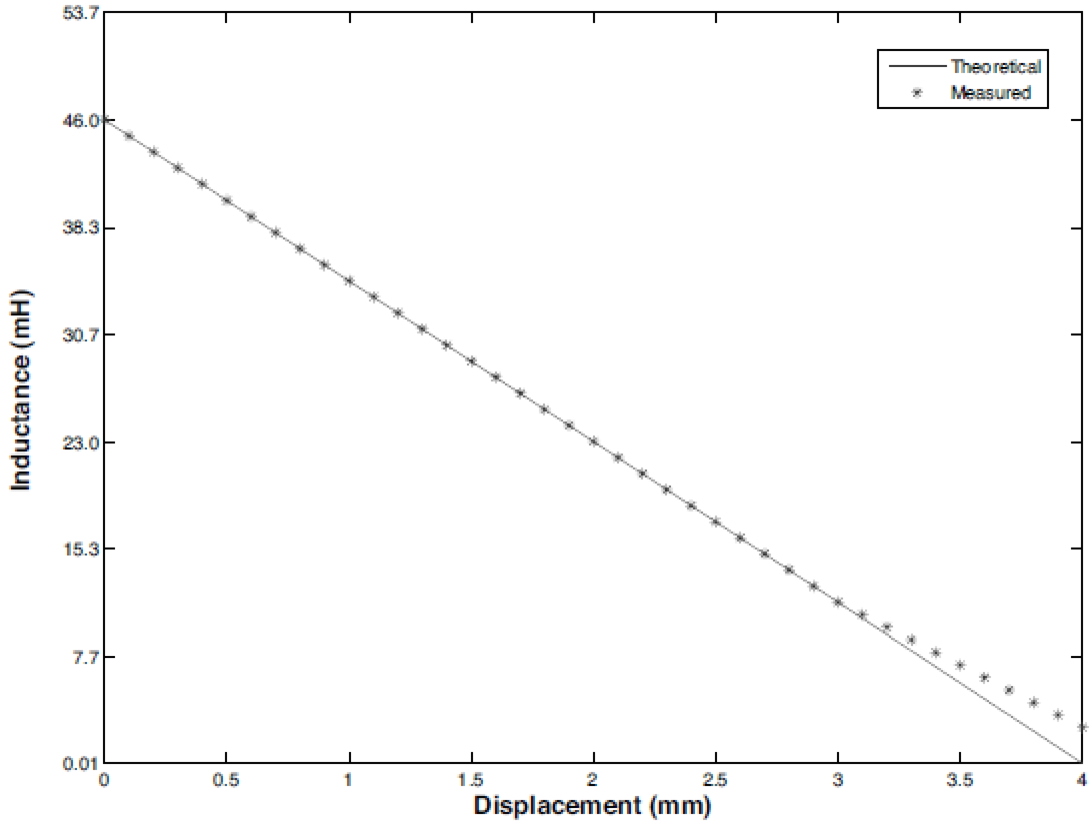
$$\boxed{L = L_1 + L_2 \quad = \quad \frac{\mu_0 N^2 A}{l}\left[\mu_r - \frac{x}{l}(\mu_r - 1)\right]}$$

$$\boxed{= \quad L_0\left[\mu_r - \frac{x}{l}(\mu_r - 1)\right]}$$

where L is the total observed inductance and
L_0 is the inductance of the coil with an
air core (minimum inductance)

plot of *L* as a function of the displacement *x*

inductance varies linearly from a maximum value L_{max} (inductance of the coil with iron core) to a minimum value L_0



Position of the iron core as a function of the applied pressure:

Step-1: In the present prototype, the pressure acts on the iron core in the upward direction.

$$P_{min} = \frac{F_{min}}{A}$$

Step-2: Accordingly, a minimum force $F_{min} = mg$ must be applied, where m is the mass of the iron core and g is the acceleration of gravity.

Step-3: The sensor cannot respond to any pressure less than P_{min} equal to 0.3 kPa in the present prototype

Step-4: Pressures larger than P_{min} will result in a force that will compress the vertical spring

The net force acting to compress the spring will be given by

$$\boxed{F = kx = (P - P_{min})A}$$

where k is the spring constant and P is the pressure acting on the sensor

The displacement x of the iron core will be given as a function of pressure by

$$\boxed{x = \frac{(P - P_{min})A}{k}}$$

$$x = \frac{(P - P_{min})A}{k}$$

Applied pressure as a function of the observed inductance L:

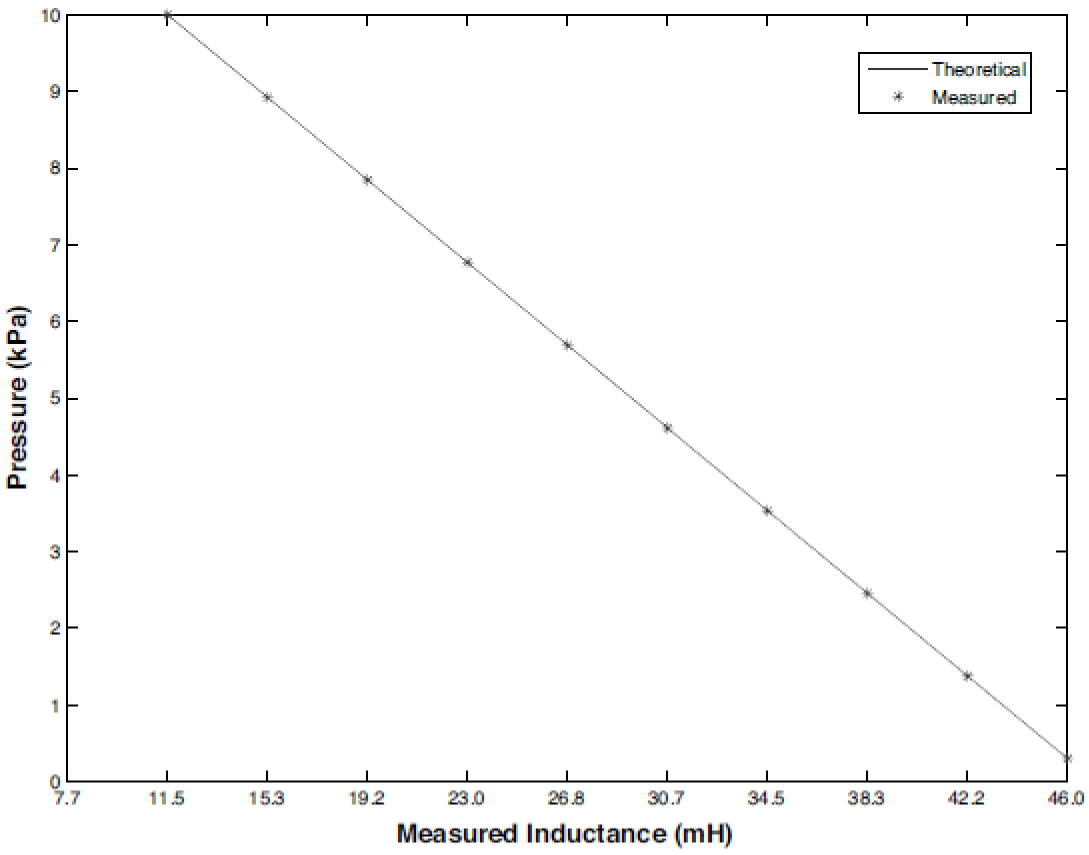
We obtain a relationship between L and the applied pressure:

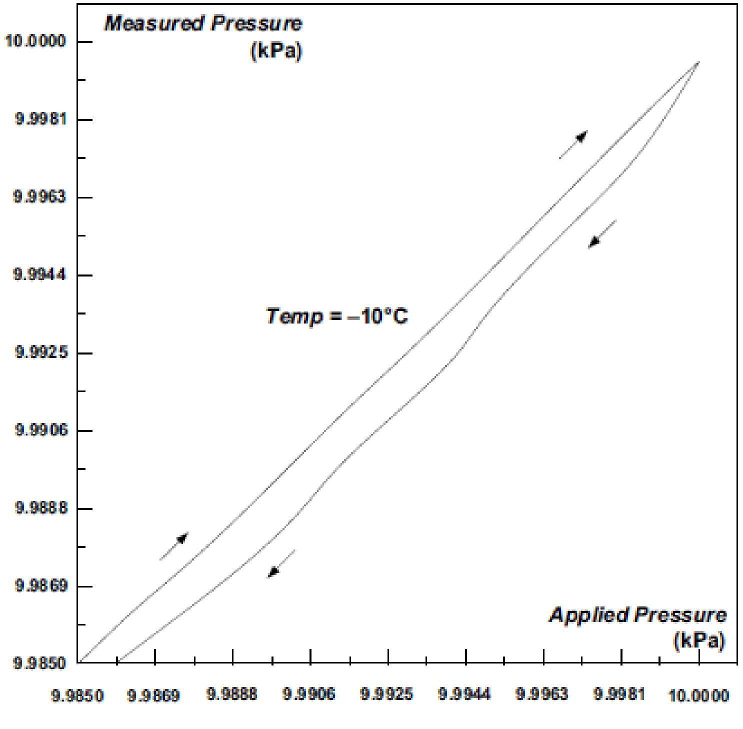
$$L = L_0 \left[\mu_r - (\mu_r - 1) \frac{(P - P_{min})A}{kl} \right]$$

Solving for P, we obtain

$$P = P_{min} + \frac{kl}{A} \left(\frac{\mu_r - L/L_0}{\mu_r - 1} \right)$$

Pressure P as a function of the measured inductance L.





(a)

Pressure hysteresis:

The hysteresis in the values of the calculated pressure was determined by cycling the pressure applied to the sensor at a fixed temperature and plotting the measured pressure versus the actual applied pressure

The maximum hysteresis error was found to be +/-0.05%

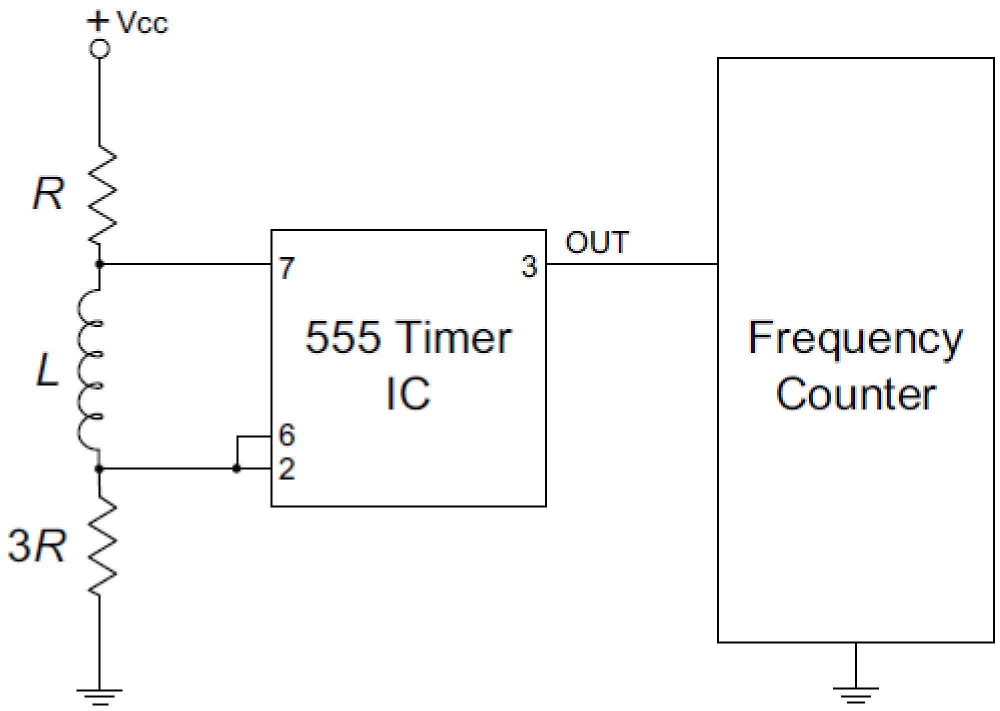
Temperature hysteresis:

The maximum temperature hysteresis error is about +/- 1%

Susceptibility to mechanical shocks:

If the sensor is shocked in the vertical direction, the iron core will be momentarily displaced, and it was observed that a "recovery time" is needed for the iron core to return to its original position

Sensor Interface Circuit



Ultrahigh Sensitivity Pressure Sensors

Recent trends in **earthquake monitoring** and prediction have created a requirement for a highly sensitive vibration detector.

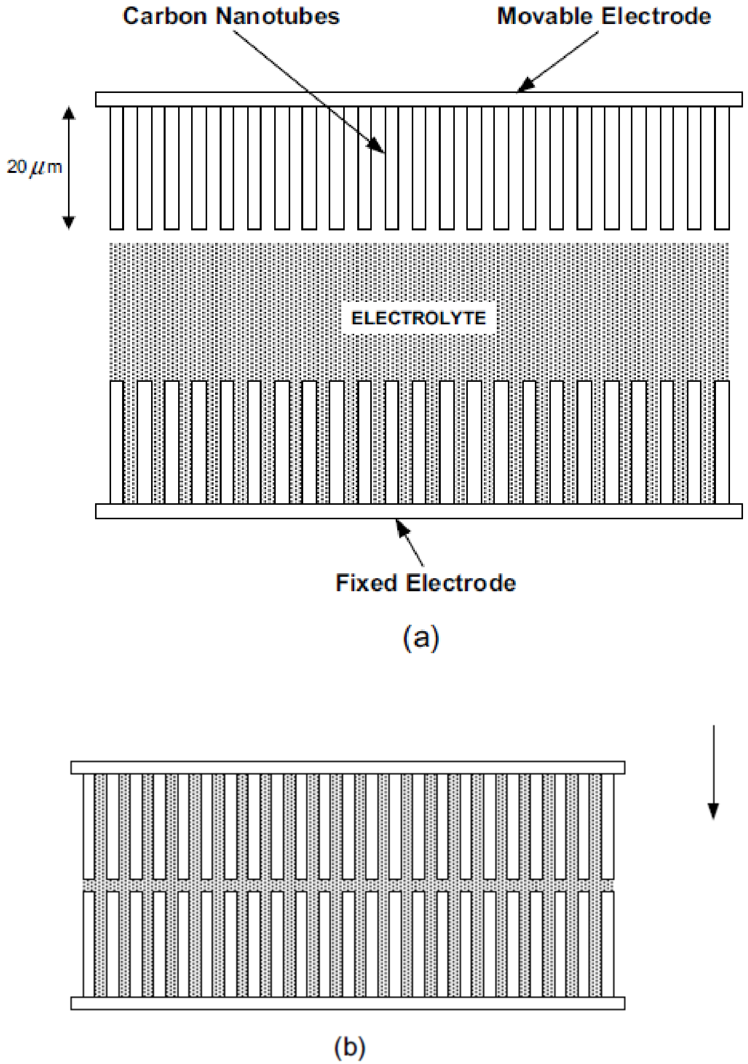
In addition, a **highly sensitive pressure sensor** (a sensor with a capability to detect pressures of less than one Pascal) will be very useful for a new class of biological and molecular sensing applications

Structure

Step-1: The basic idea behind the new sensor is to create a transduction mechanism that uses a variable ultracapacitor rather than a variable capacitor

Step-2: In this mechanism, an extremely small displacement of 20 μm (less than the width of a human hair) triggers a substantially large variation in capacitance.

Step-3: (a) An ultracapacitor consisting of two electrodes is assembled such that one electrode is fixed and is fully immersed in the electrolyte while the other electrode is movable and is initially positioned outside of the electrolytic solution

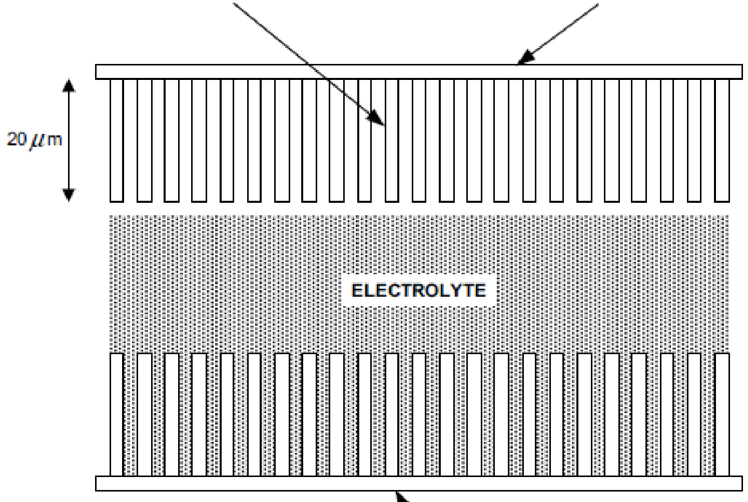


Structure

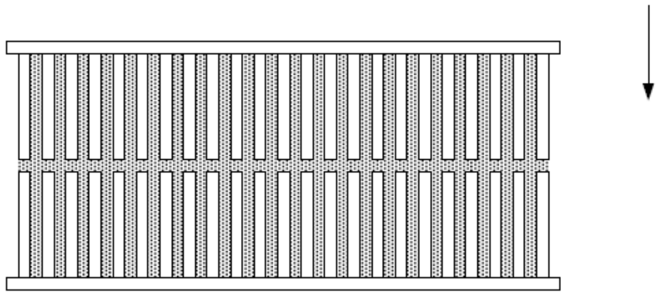
Step-4: Each electrode consists of a stainless steel plate on which carbon nanotubes of a length of approximately 20 μm are grown

Step-5: (b) As pressure or vibration is applied, the movable electrode travels downward and dips into the electrolytic solution

Step-6: As the electrode travels a distance of 20 μm(the length of the carbon nanotubes), the capacitance increases from zero to full capacitance (approximately 54 μF

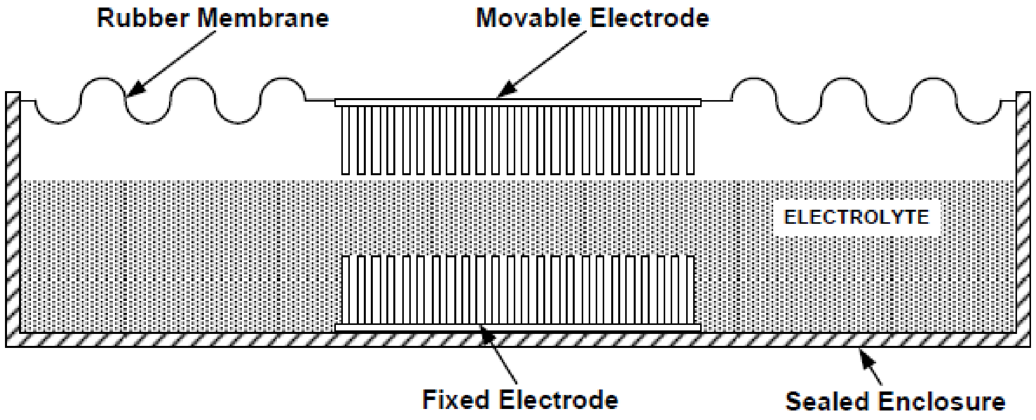


(a)


(b)

Mechanical Structure

Step-1: Figure is a mechanical diagram showing the actual construction of the sensor.



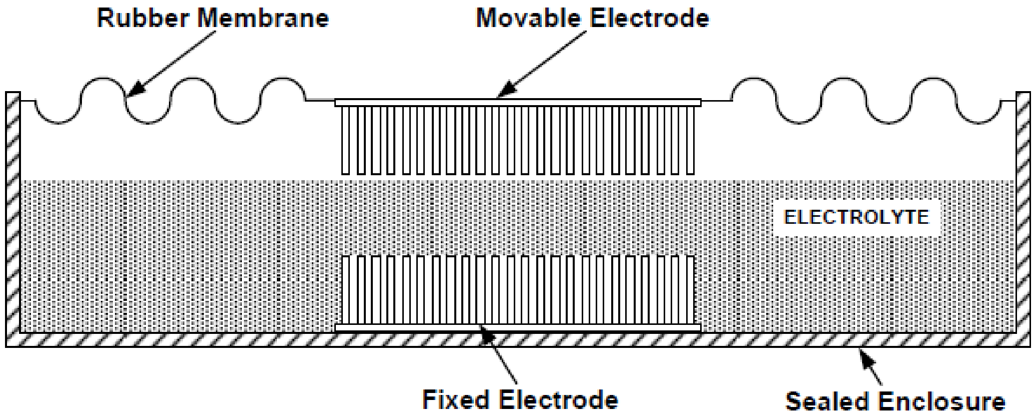
Step-2: The rubber membrane to which the movable electrode is attached acts as a spring mechanism that permits the movable electrode to retreat back to its original position.

Step-3: The rubber membrane used is actually conductive rubber, and therefore there is no need to connect a wire terminal directly to the movable electrode

Mechanical Structure

Step-4: The fixed electrode (not shown in the picture) is mounted underneath the movable electrode and is connected to its own terminal.

Step-5: The entire sensor is housed inside an off-the-shelf stainless steel enclosure that provides two external terminals for easy connection to other circuitry.



Theory

Sensing of pressure:

The surface area A of the CNTs that is immersed in the electrolyte will be given by

$$\boxed{A = N \times 2\pi r x}$$

where N is the total number of CNTs on the surface of the electrode,
r is the radius of one carbon nanotube, and
x is the displacement of the electrode

The overall capacitance C of the ultra-capacitor is a series combination of the capacitances at each of the electrode–electrolyte interfaces

$$\boxed{C = \frac{1}{2}\,\frac{\varepsilon_0 \varepsilon_r A}{d}}$$

The pressure acting on the sensor is simply given by the ratio

$$\boxed{P = \frac{F}{A_{electrode}}}$$

where $A_{electrode}$ is the area of the movable electrode.

Sensing of vibrations:

When the sensor is subjected to vibration, the moving electrode can be modeled as a forced harmonic oscillator

$$x(t) = \frac{F_{max} \sin \omega t}{m\sqrt{(\omega_0^2 - \omega^2)^2 + \beta^2 \omega^2}}$$

where *m* is the mass of the oscillator (the electrode),

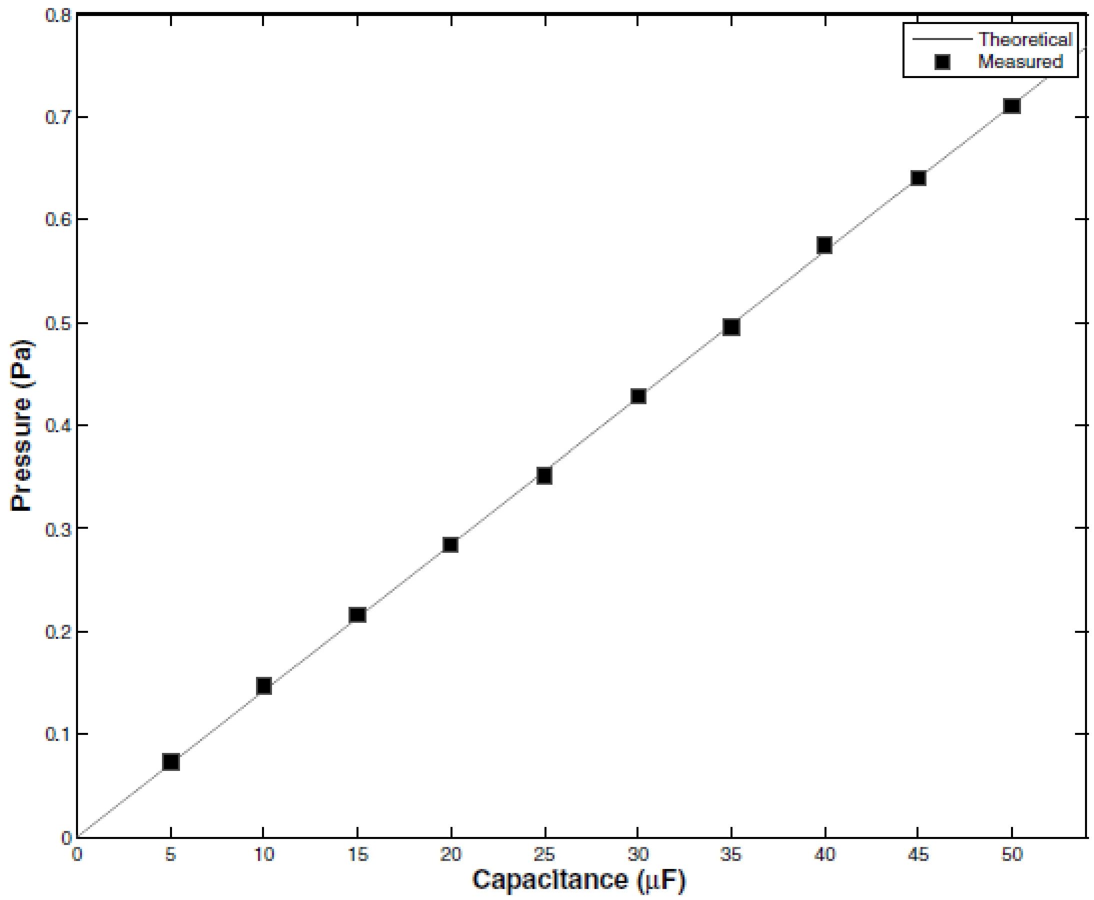
$\omega_0 = \sqrt{k/m}$ is the natural frequency of oscillation

β is the damping coefficient

$F_{max} \sin \omega t$ is the sinusoidal force acting on the oscillator.

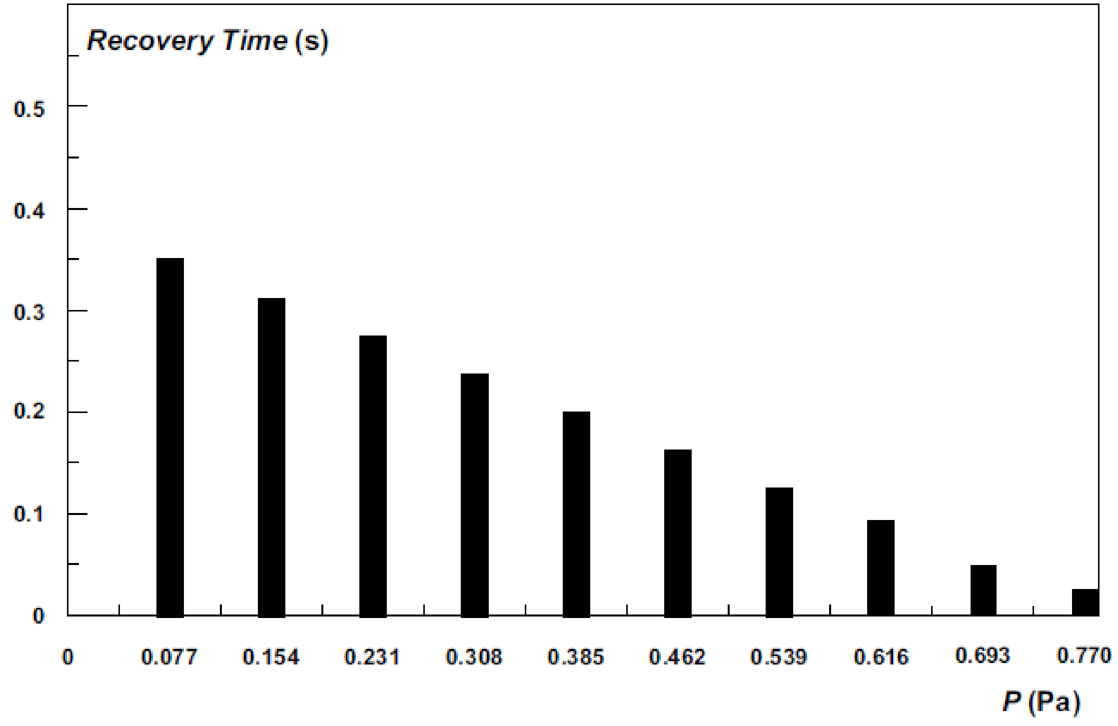
Pressure measurement:

Pressure acting on the sensor as a function of the measured capacitance



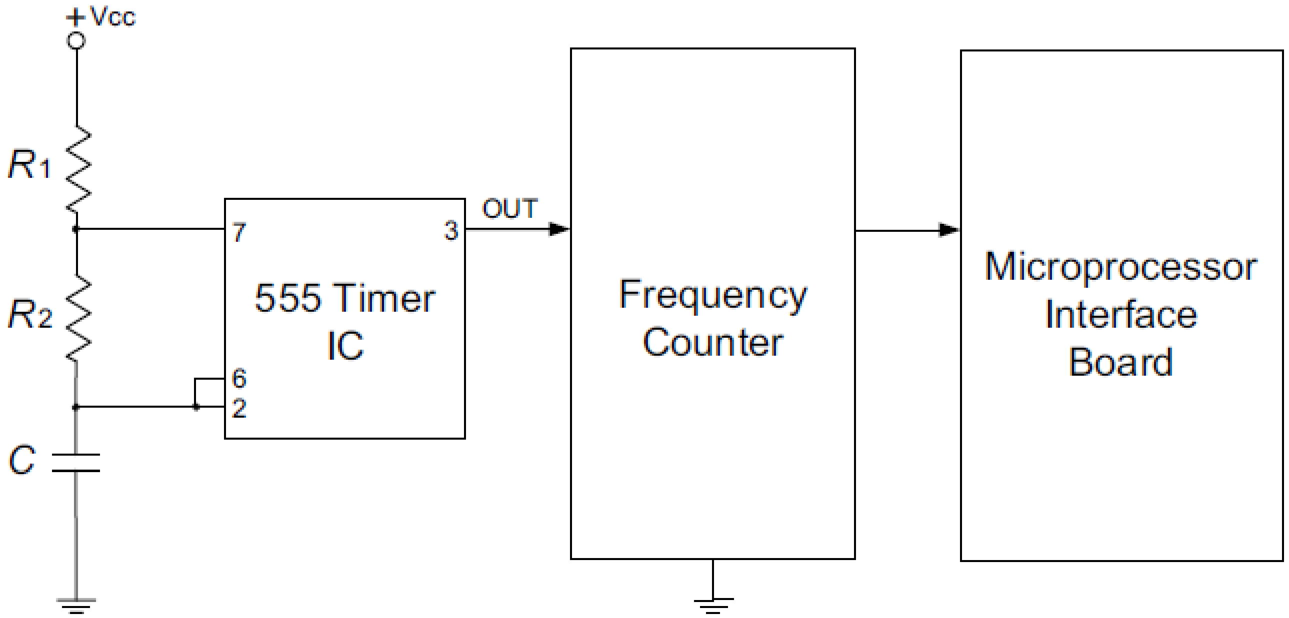
Acceleration measurement:

The sensor was subjected to vibrations at a frequency of 14 Hz on the electrodynamic shaker



After-shock recovery time as a function of the applied pressure

Block diagram of the interface circuit used to measure the capacitance *C*.



1) True or false: novel new microscale capacitive pressure sensors are based on the displacement of a plate.

Ans: False. These new sensors are based on the deformation of a droplet of mercury

2) True or false: both capacitive and inductive pressure sensors are linear.

Ans: False.

Only the inductive pressure sensors are linear.
Capacitive pressure sensors are usually nonlinear.

3) Which scientific principle is behind ultraminiature, ultrasensitive pressure sensors?

Ans: The use of a variable ultracapacitor.

Thank You

18EE8732:Micro and Nano Scale Sensors and Transducers

MODULE – 2: Motion & Acceleration Sensors

Prepared By,

Shreeshayana R

Electrical and Electronics Engineering

ATME College of Engineering, Mysuru

CONTENTS

Module-2

Motion and Acceleration Sensors: Ultrahigh Sensitivity, Wide Dynamic Range Sensors, Other Motion and Acceleration Microsensors.

Gas and Smoke Sensors: A CO Gas Sensor Based on Nanotechnology, Smoke Detectors.

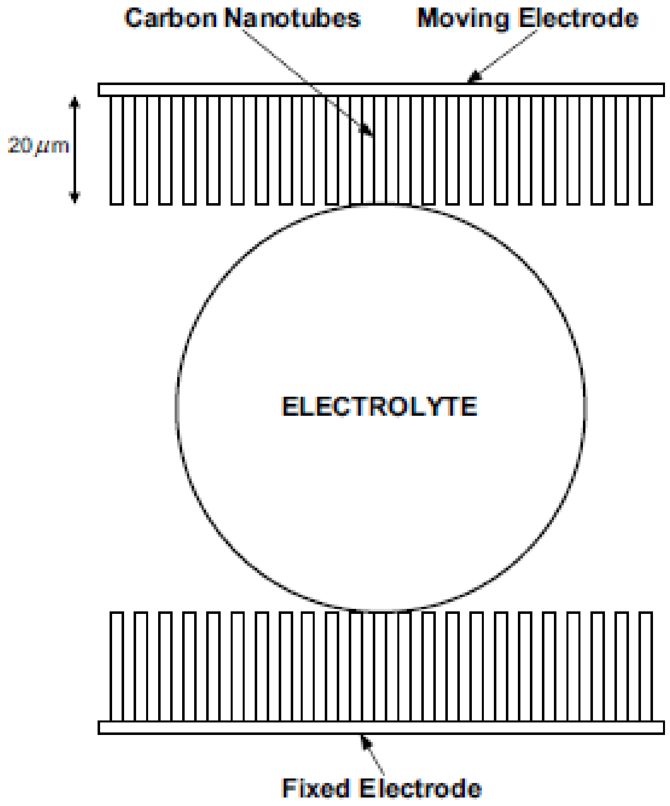
Ultrahigh Sensitivity, Wide Dynamic Range Sensors

A number of new applications, such as self-guided small projectiles and autonomous surveillance airplanes, have created a requirement for a highly sensitive yet very small acceleration sensor.

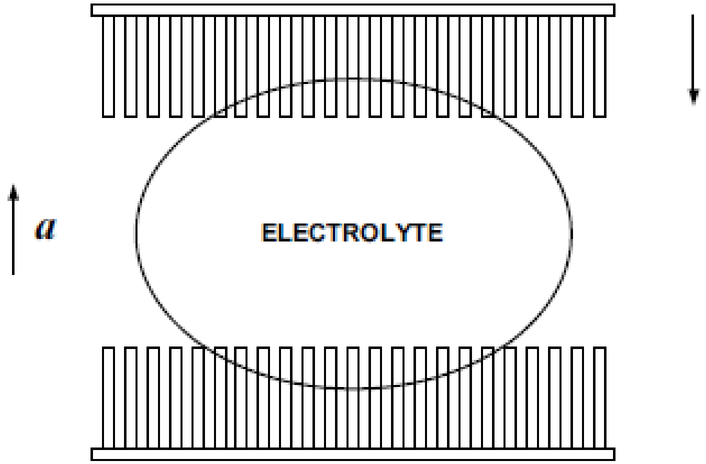
A new **miniature acceleration sensor** with a radical new design was recently introduced.

The sensor offers a very large **dynamic range and high sensitivity**.

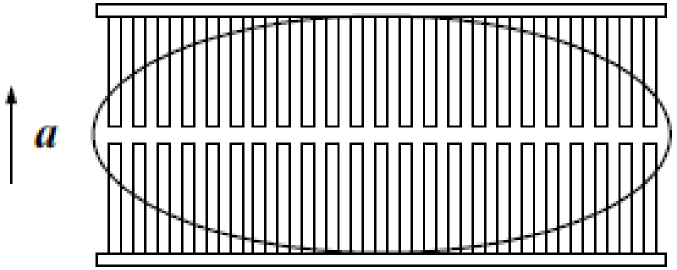
Structure



(a)



(b)



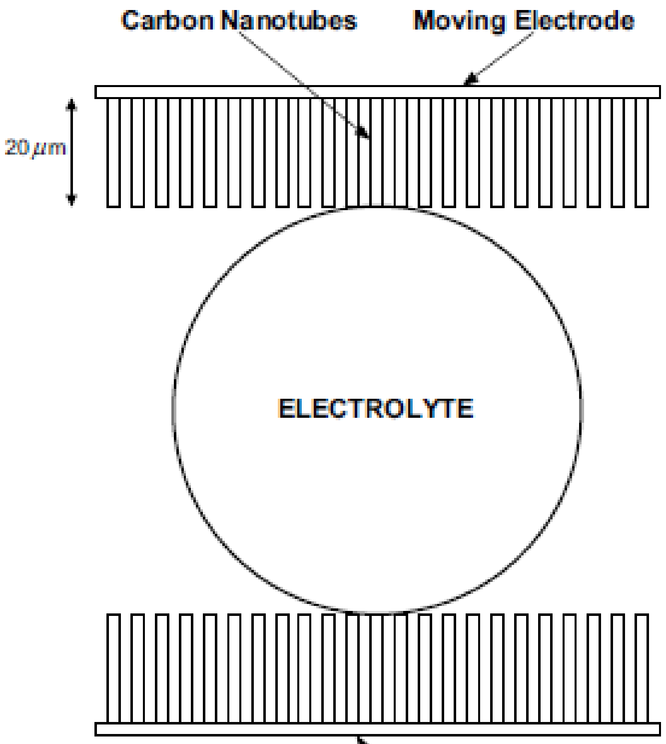
(c)

Structure

Step-1: The new acceleration sensor is based on the concept of creating a variable ultra capacitor structure that consists of one **small droplet of electrolyte** that is positioned between **two carbon nanotube (CNT) electrodes.**

Step-2: The CNT electrodes remain outside of the electrolyte due to their hydrophobic nature.

Step-3: Under acceleration, however, **the inertial forces push the CNT electrodes into the electrolyte** and the typical capacitance of an ultra capacitor is obtained.



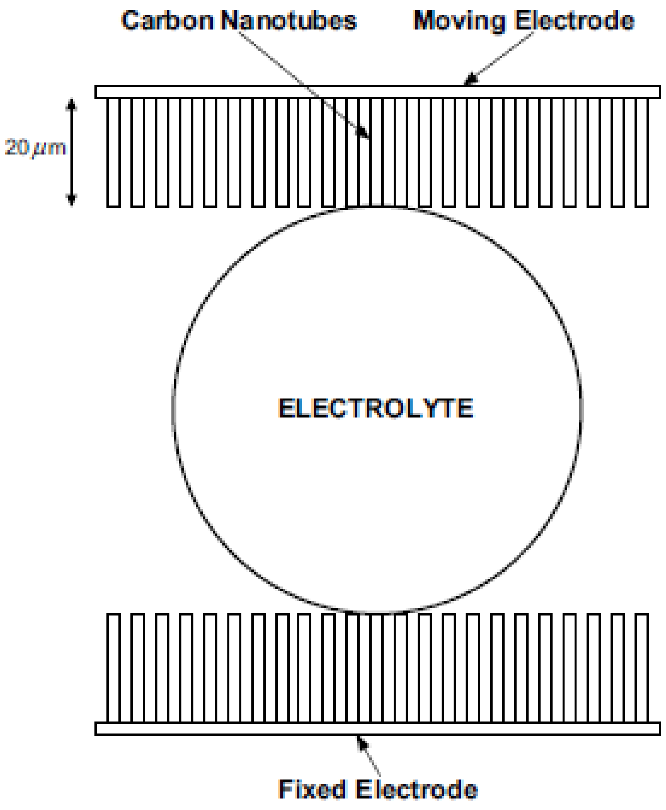
(a)

Structure

Step-4: Figure (a), a small droplet of electrolyte (fluid with high ionic conductivity) is placed between two electrodes on which **CNTs of a length of 20 μm are grown.**

Step-5: One electrode is fixed while the other is movable, as shown.

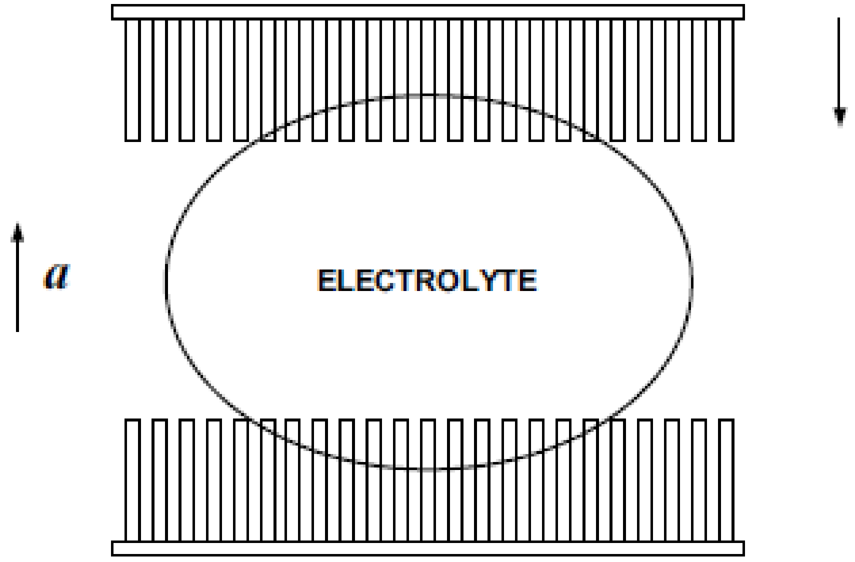
Step-6: Since the weights of the droplet and the electrodes are very small, and since CNTs are superhydrophobic, the CNTs **do not penetrate the electrolyte when the mechanism is at rest.**



(a)

Structure

Step-7: In Figure (b), as acceleration occurs along the axis of the device (here, vertically, upward), the inertial forces created by the droplet and the moving electrode cause the CNTs to penetrate the electrolyte

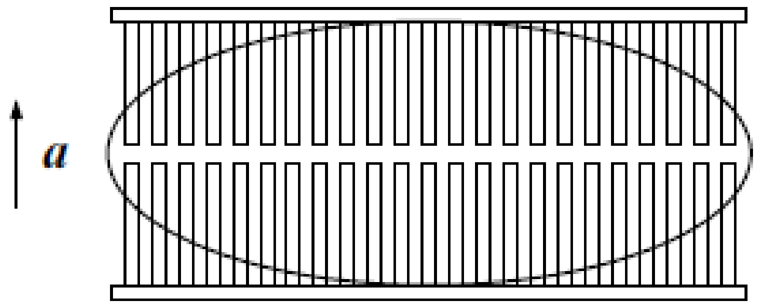


(b)

Structure

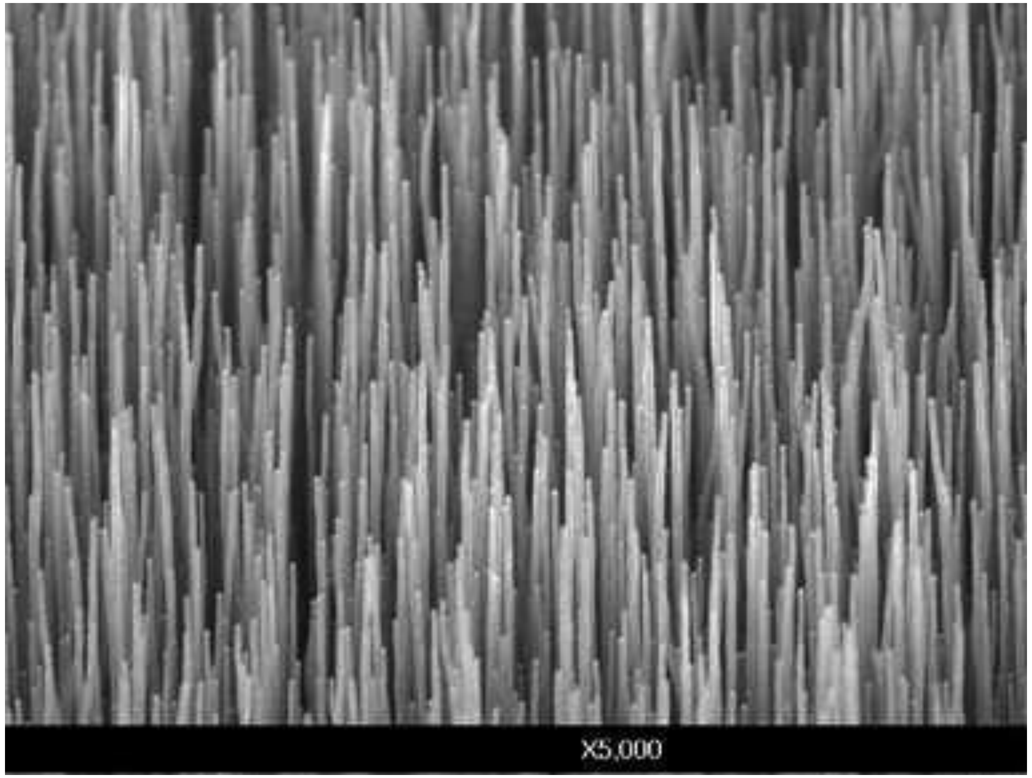
Step-8: The forces created due to inertia further increase at higher accelerations, and the penetration of the CNTs into the electrolyte **<u>increase to a maximum.</u>**

The capacitance of the thus-formed ultracapacitor increases to a substantially high value



(c)

Structure



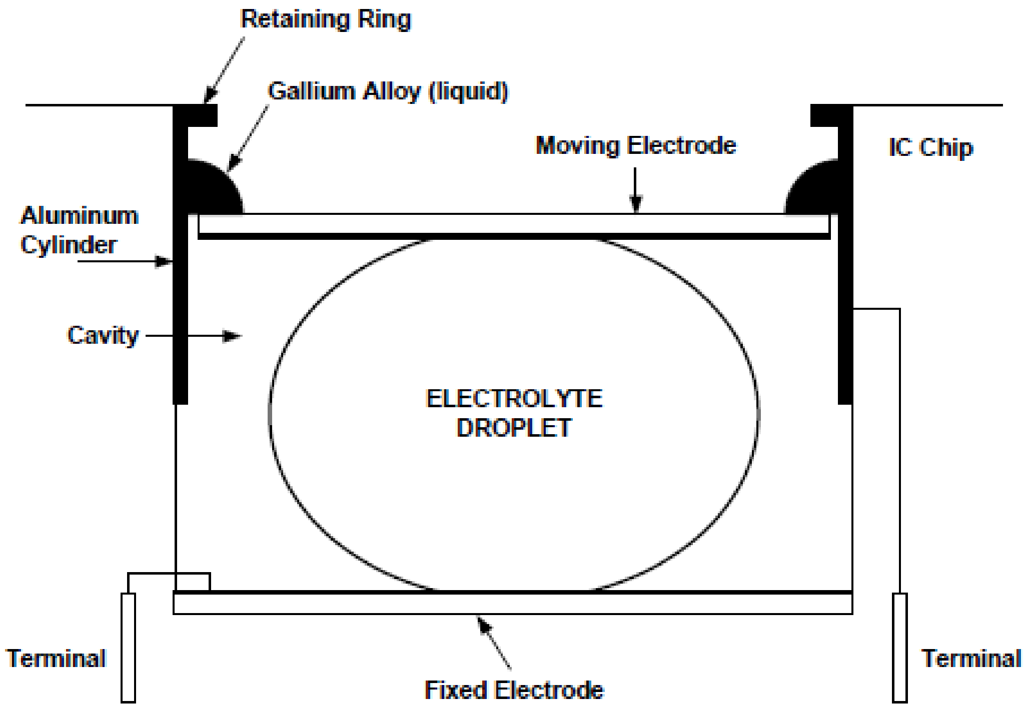
Multiwalled carbon nanotubes of an average diameter of 250 nm and a length of about 20 μm, grown on a stainless steel electrode.

Mechanical Structure

Step-1: the electrolyte droplet, the fixed electrode, and the moving electrode are placed inside the cavity in the SOIC chip

Step-2: A very thin aluminum cylinder with a height of approximately one-half that of the cavity is also inserted in the cavity.

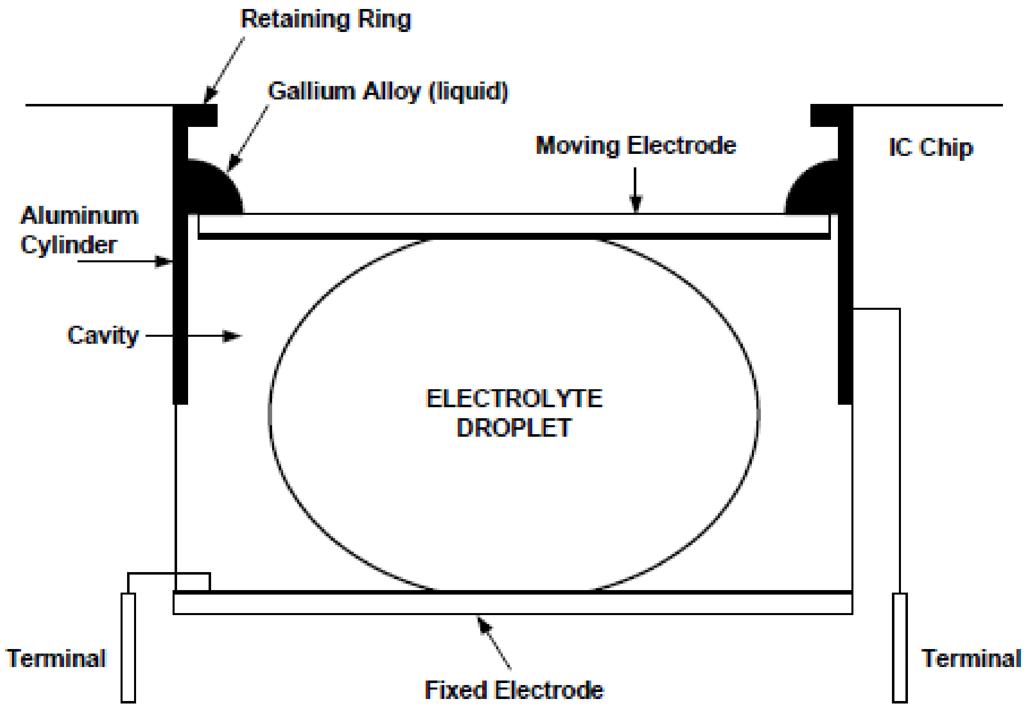
The purpose of the cylinder is to act as a **contact terminal for the moving electrode.**



Mechanical Structure

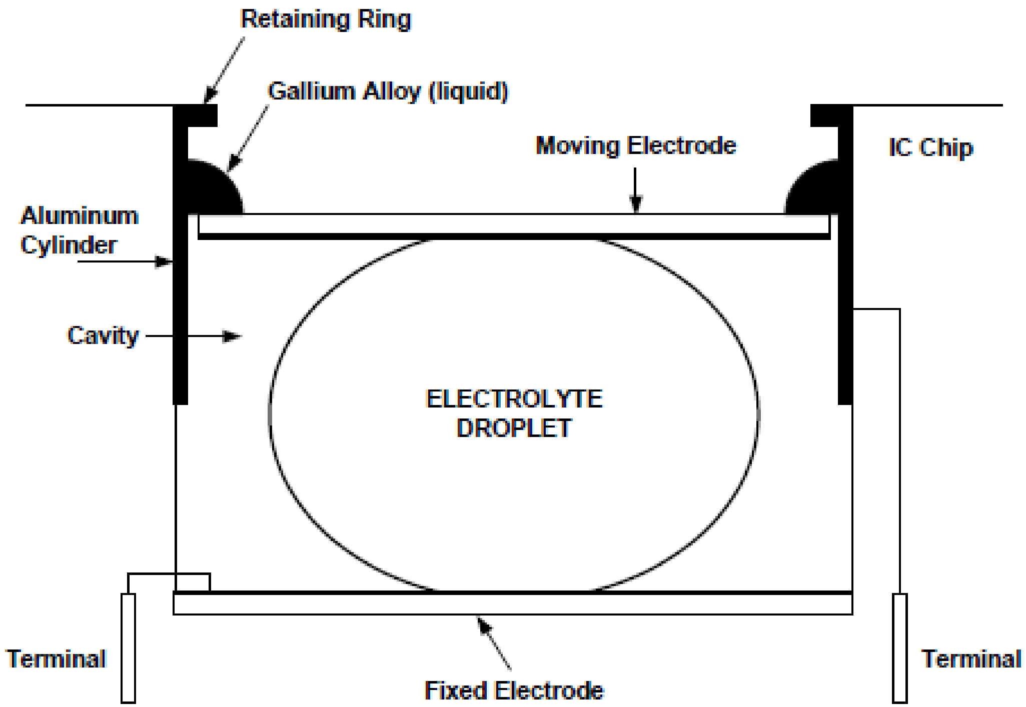
Step-3: **<u>"Liquid Metal"</u>** is placed on top of the moving electrode and serves to establish **electrical contact between the electrode and the aluminum cylinder. The "LiquidMetal" is a gallium alloy that is normally liquid at temperatures above −20◦C**

Step-4: A steel ring is placed on top of the cavity and serves to retain the moving electrode, and hence the electrolyte droplet, inside the cavity



Mechanical Structure

Step-5: The electrolyte used in the present application is **propylene carbonate (solvent)** in which an ionic salt is dissolved (a typical ultracapacitor electrolyte



Observations

First: It is to be pointed out that propylene carbonate **has a boiling point of 240◦C.** Accordingly, any possible evaporation of the electrolyte will occur only at elevated temperatures. **The sensor was indeed tested at temperatures of up to 80◦C, and no evaporation of any kind was observed.**

Second: The second issue concerns the possible effect of the inclination angle on the measurement provided by the sensor. It is to be pointed out that the weight of the electrolyte droplet is only 5 mg, and hence the surface tension forces are far larger than the deformation forces that exist due to the weight.

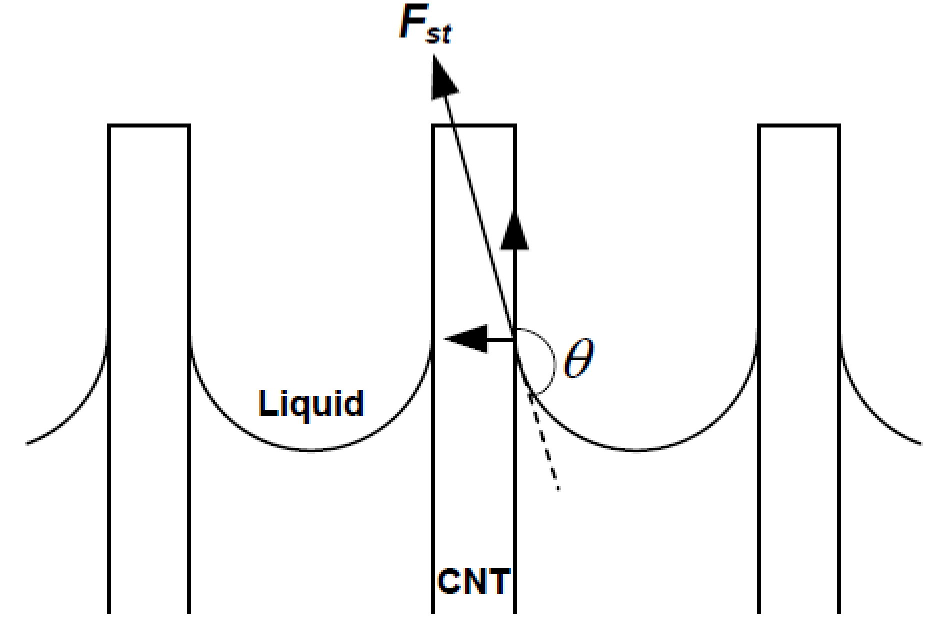
Comparison of the new sensor to other known types of capacitive Acceleration sensors.

	Sensitivity	Dynamic Range	Size
New sensor	2.27 nF/g	2200 g	3 mm (dia) x 2 mm (h)
Other capacitive acceleration sensors	typically a few pF/g	typically a function of the size	few cm up to a few hundred cm (for each dimension)

Theory

For each CNT, the hydrophobic force (or force that repels the fluid away from the CNT) will be given by

$$F = 2\pi r\gamma\cos(180^\circ - \theta)$$

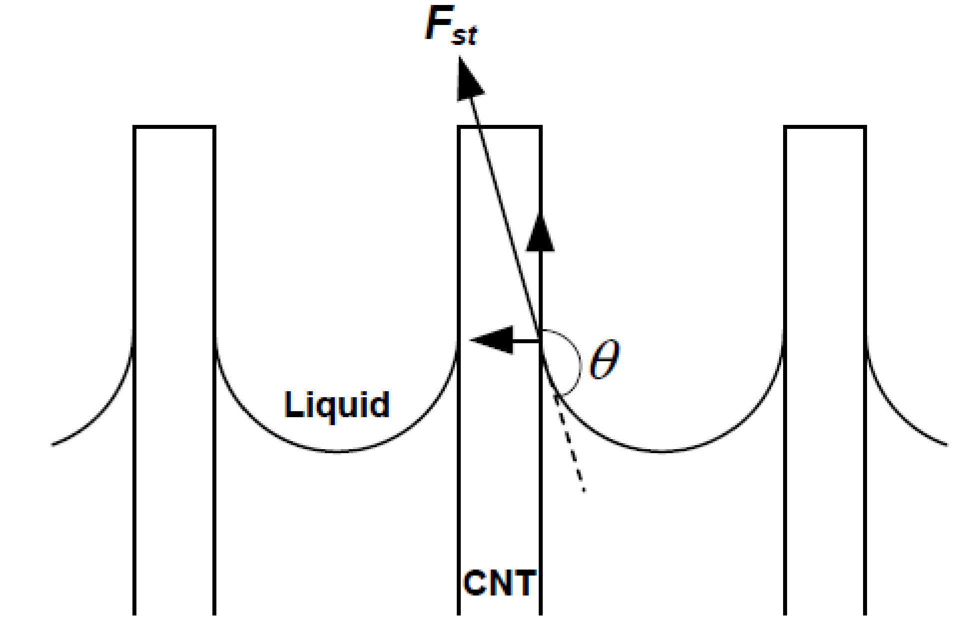


r **is the radius of one CNT,**
γ **is the surface tension of the fluid,**
θ **is the liquid–solid contact angle, and the product**
$2\pi r\gamma$ represents the surface tension force

Theory

Newtonian force $F = ma$ must be balanced by the total hydrophobic force, that is,

$$F_{total} = ma = 2\pi r N \gamma \cos(180^\circ - \theta)$$



The capacitance of the electrode–electrolyte interface will be now given by

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

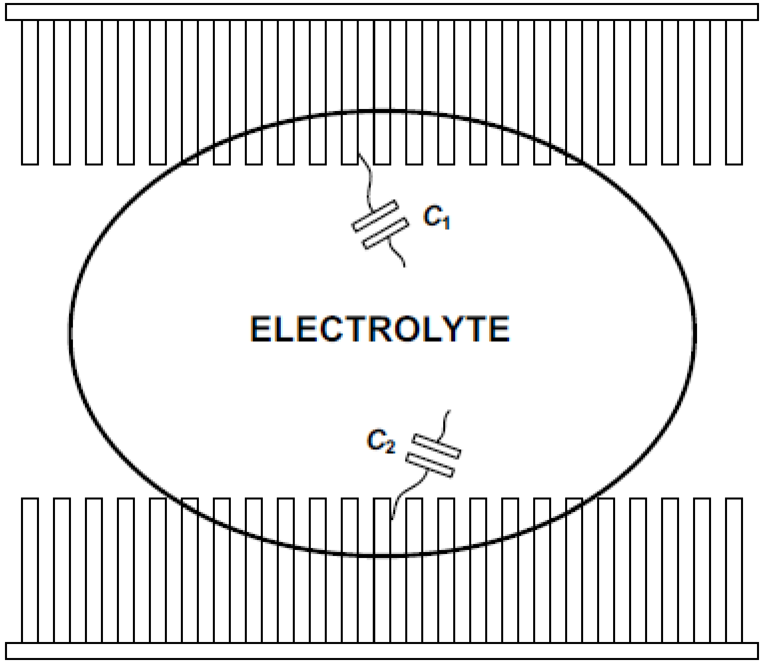
$$A = 2\pi r \sum_{i=1}^{N} x_i$$

The surface area A of the CNTs

where x_i is the immersion depth of any given CNT.

Structure

The total capacitance of the ultracapacitor is the series combination of the capacitances at the two interfaces $C1$ and $C2$.



$$C = \frac{\varepsilon_0}{d}\left(2\pi r \sum_{i=1}^{N} x_i\right)$$

In general, C_2 will be larger than C_1, since the lower interface is acted upon by **<u>both the upper electrode and the electrolyte droplet</u>**

the series combination of C_1 and C_2 can be expressed as

$$C_{total} = K\frac{\varepsilon_0}{d}\left(2\pi r \sum_{i=1}^{N} x_i\right)$$

where K is a constant that ranges from 1 at very small accelerations (where $C_2 \gg C_1$)

0.5 at very high accelerations (where $C_2 \approx C_1$)

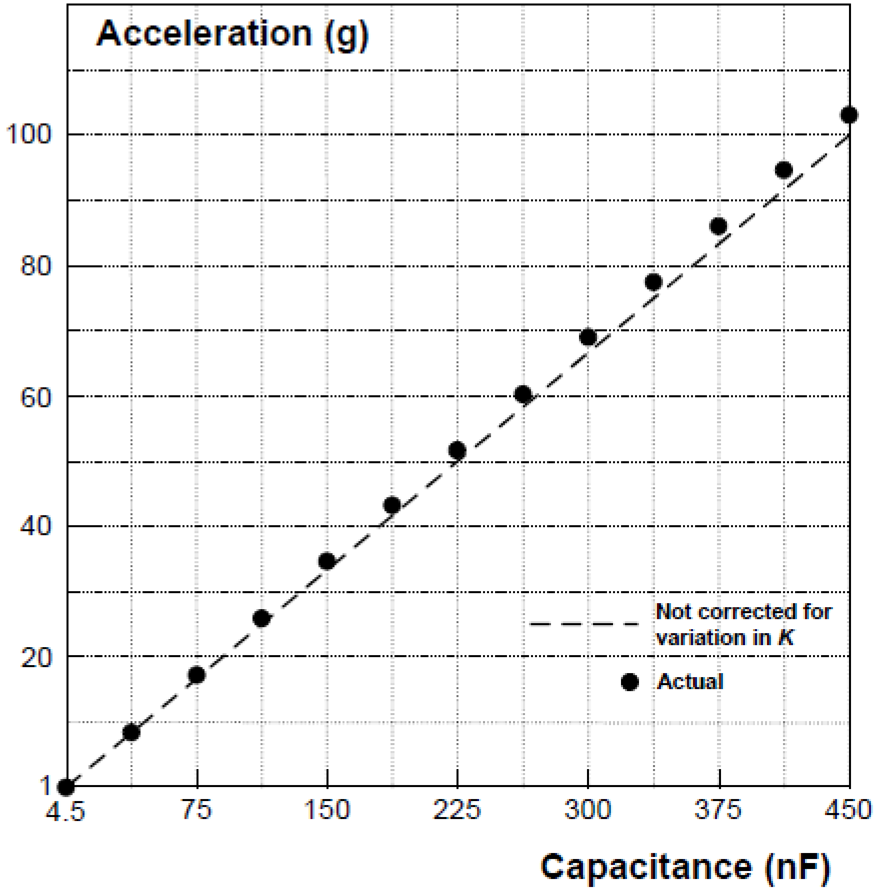
$$ma = N\gamma\cos(180^\circ - \theta)\left(\frac{dC_{total}}{K\varepsilon_0\sum_{i=1}^{N} x_i}\right)$$

$$a = -\frac{dN\gamma\cos\theta}{Km\varepsilon_0\sum_{i=1}^{N} x_i} C_{total}, \quad \theta > 90^\circ$$

Structure

Measurement of acceleration

Capacitance of the sensor during the acceleration pulse and calculating the value of the acceleration

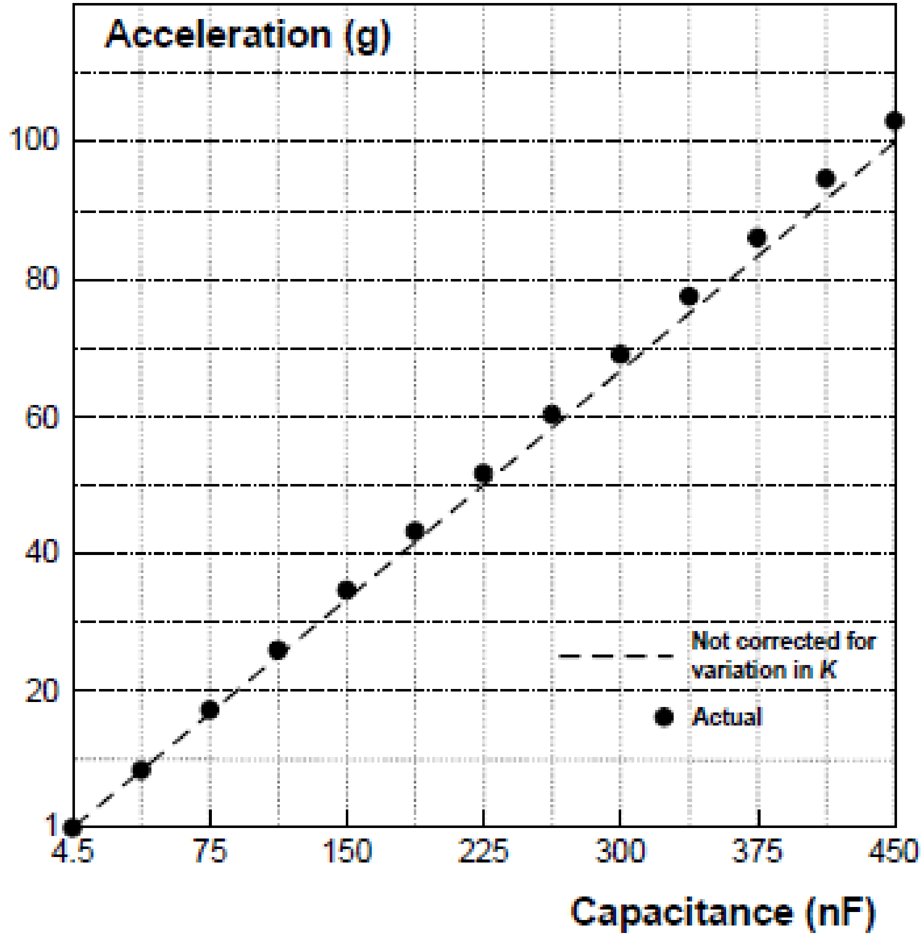


Measured and theoretical acceleration in the range of 0.0002 g to 1 g as a function of the measured capacitance.

Structure

Measurement of acceleration

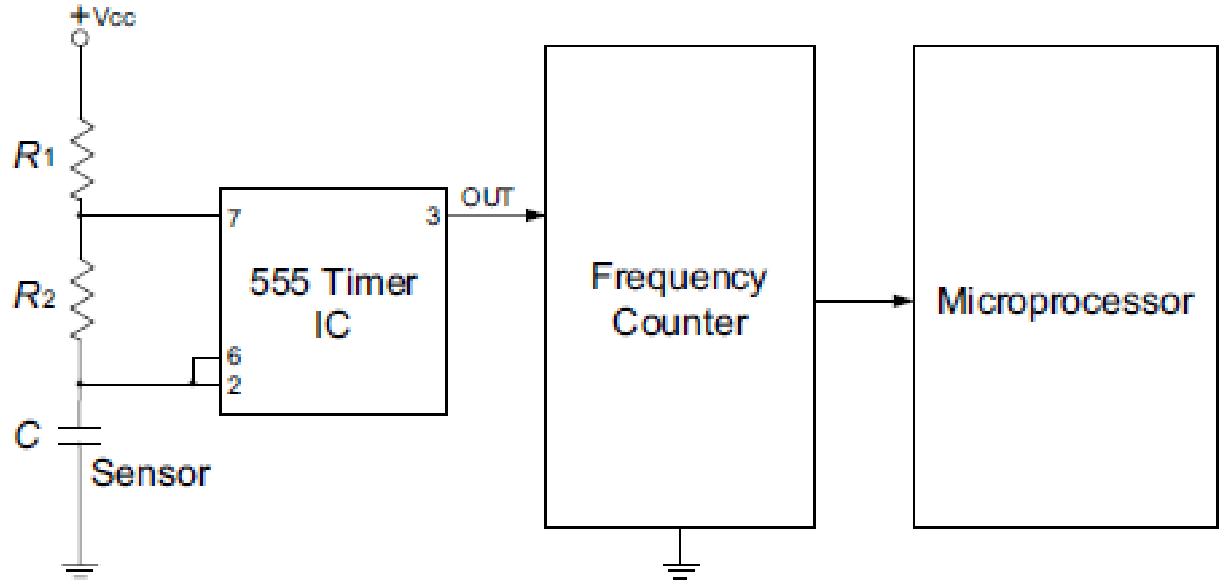
Capacitance of the sensor during the acceleration pulse and calculating the value of the acceleration



Acceleration in the range of 1 g to 100 g as a function of the measured capacitance.

Structure

Block diagram of the interface circuit used for measuring the capacitance *C* of the sensor in real time.



MEMS acceleration sensor described in this chapter has an ultrawide dynamic rage and high sensitivity. Specifically, the sensitivity is 2.27 nF/g,

The circuit board and the 0.45-caliber bullet that were used for testing the sensor at accelerations up to 2200 g.

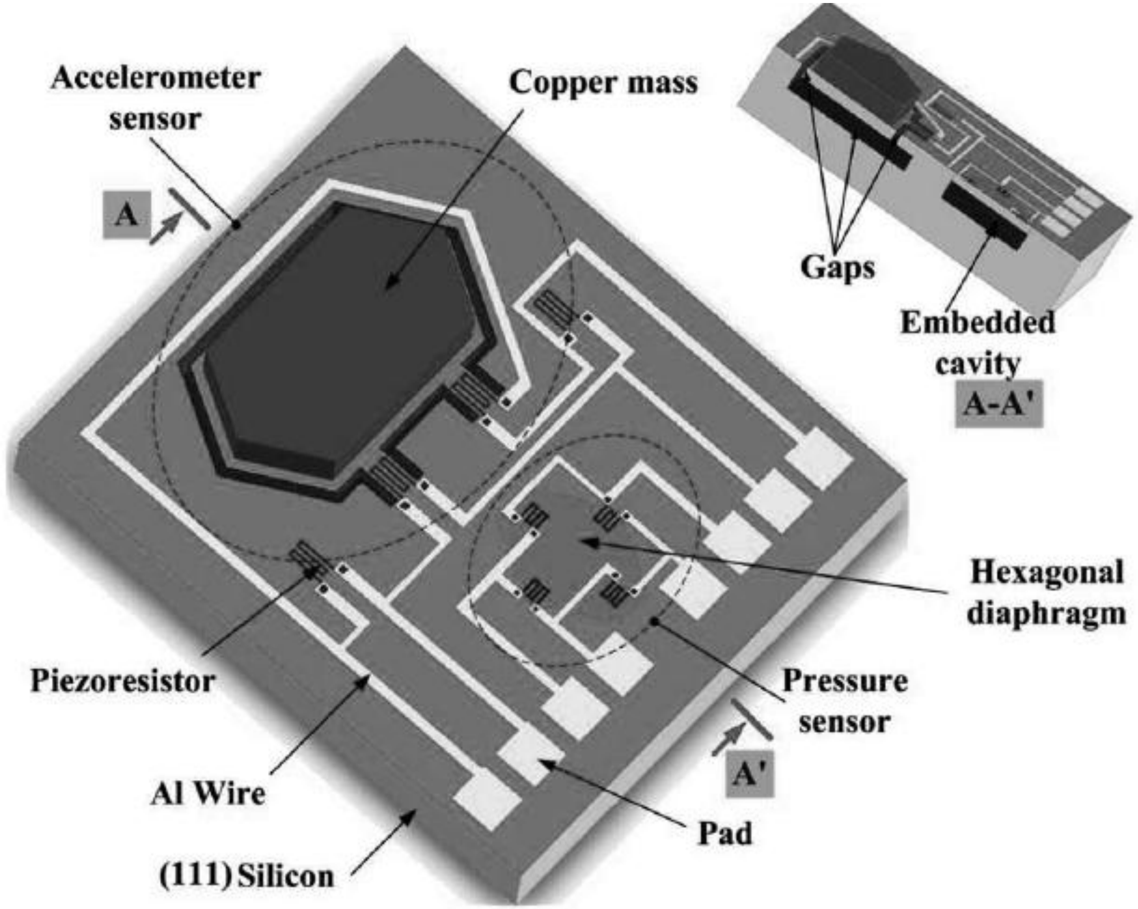
Inference: Specifically, the sensitivity is 2.27 nF/g, and the dynamic range extends from
2×10^{-4} g to 2193 g.

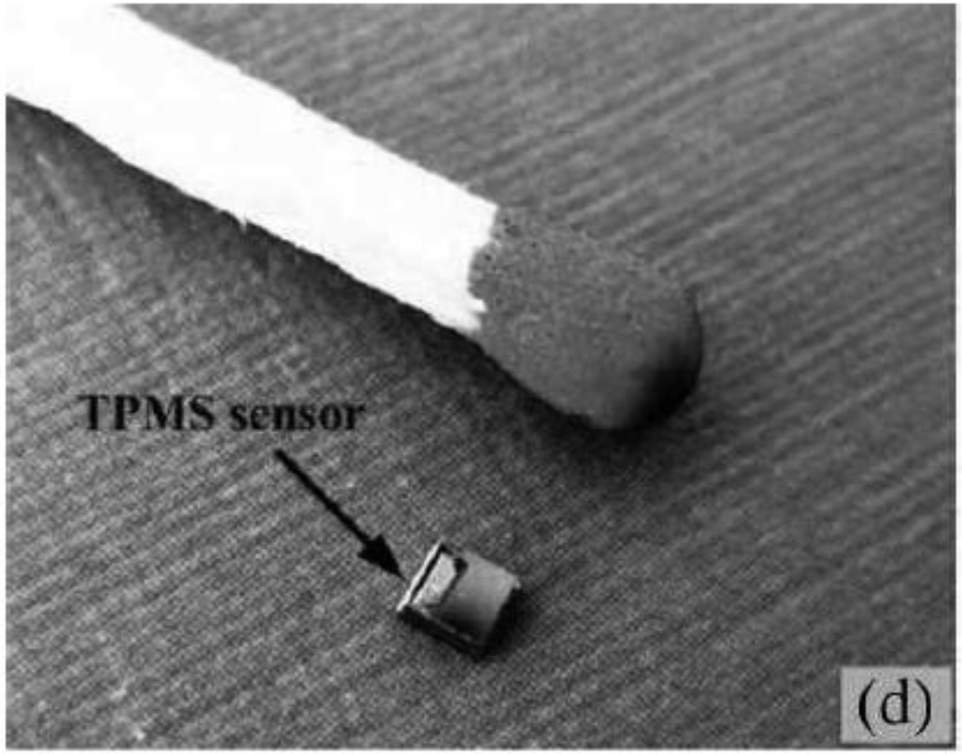
It will therefore be useful in a wide array of new applications, including **self-guided projectiles** and **autonomous surveillance aircraft**.

Other Motion and Acceleration Microsensors

Concept for a monolithic integration of pressure plus acceleration composite Tire Pressure Monitoring Sensor (TPMS) with a single-sided micromachining technology

Monolithic Tire Pressure Monitoring Sensor





Quiz

1) True or false: applications such as self-guided projectiles require an acceleration sensor with a large dynamic range and high sensitivity

Quiz

2)Which scientific principle is behind the new ultraminiature, ultrasensitive acceleration sensor described in Module-2?

Ans: The use of a variable ultracapacitor.

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