MODULE-5- Semiconductor devices and Sensors

Direct and indirect band gap, Band gap engineering, Zener Diode, LED, Photodiode, Photo Transistor, Light dependent resistor, Resistance temperature detectors (high, medium, low), Sensing mechanisms, Piezo electric Sensors, Metal Oxide Semiconductor (MOS) sensors, Hall sensor, Superconducting Nanowire Single Photon Detector, Numerical Problems.

Module - 5 Blow-up

Subtopics	Topics to be covered	Duration
Direct and indirect band gap , Band gap engineering	Direct and indirect band gap - Explanation, Difference Band gap engineering- Brief explanation	1
Zener Diode	Circuit symbol, Reverse characteristic, Mention applications	½
LED	Circuit symbol, Forward characteristic, Mention applications	½
Photo Diode	Circuit symbol, Reverse characteristic, Mention applications	½
Photo Transistor	Construction, Circuit symbol, characteristic, Mention applications	1
Light dependent resistor, Resistance temperature detectors (high, medium, low)	Light dependent resistor- symbol and mention of applications, Resistance temperature detectors-Explanation and examples for high, medium, low	1 ½
Sensing mechanisms - Piezo electric Sensors, Metal Oxide Semiconductor (MOS) sensors, Hall sensor, Superconducting Nano-wire Single Photon Detector,	Principle Construction and working and mention of applications of each	2
Numerical Problems	Resistance Temperature Detectors (Resistance at a given temperature $R=R_0(1+\alpha(t-t_0))$. Photo Diode Power Responsivity R_λ , Voltage mode Hall Sensor Sensitivity – $S_V= R_H/d$	1

Direct and indirect band gap:

Based on the composition of semiconductors they are classified as:

(i) Elemental semiconductors
(ii) Compound semiconductors.

(i) Elemental Semiconductors:

The elemental semiconductor is made of single element from the fourth column elements. Germanium and Silicon are the important examples for elemental semiconductors, these are also known as **indirect band gap semiconductors**. Here the recombination of an electron from the conduction band with a hole in the valence band takes place via traps. In this process, the phonons are emitted while recombination and they heat the lattice.

(ii) Compound Semiconductors:

The compound semi- conductors are made combining oy third and fifth column elements (or) second and sixth column elements. GaAS, InP are important examples for compound semiconductors, these are also known as **direct band gap semiconductors**. Here the recombination of electron and hole takes place directly and its energy difference is emitted in the form of photons in the visible (or) infrared range.

Since the lifetime of the charge carrier is so small, the current amplification is small. Hence these diodes are not suitable for making transistors and ICs, rather they are used in making LEDs and LASER diodes.

S.No	Elemental Semiconductors	Compound Semiconductors
1.	They are made of single element Eg: Ge,Si	They are made of compounds Eg: GaAs, GaP, MgO etc
2.	They are called as indirect band gap semiconductors.i.e., electron-hole recombination takes place through traps, which are present in the band gap.	They are called as direct band gap semiconductors. i.e., electron-hole recombination takes place directly with each other.
3.	Here, heat is produced during recombination.	Here, the photos are emitted during recombination.
4.	They are used for the manufacture of diodes and transistors., etc.	They are used for making LED's, laser diodes,IC's etc.

<u>Band gap engineering:</u>

Energy band in solids In the case of a single isolated atom, there are various discrete energy levels. In solids, the atoms are arranged in a systematic space lattice and neighboring atoms influence each atom. The closeness of atoms results in the intermixing of electrons of neighbouring atoms. Due to this, number of permissible energy levels increases. Hence in the case of a solid, instead of a single energy level associated with single atom, there will be bands of energy levels. A set of such closely packed energy levels is called an energy band. The bands of energy levels are referred to the entire solid as a whole and not to the single atom.

In some materials, the valence electrons are loosely attached to the nucleus. Even at room temperature, some of the valence electrons can leave the valence band. These are called as free electrons. They are responsible for conduction of current in a conductor and are henceforth called as conduction electrons. The band occupied by these electrons is called conduction band. This band may be an empty band or partially filled band.

The separation between valence band and conduction band is known as forbidden energy gap. If an electron is to be transfered from valence band to conduction band, external energy is required, which is equal to the forbidden energy gap.

Band Gap in solids:

Insulators:

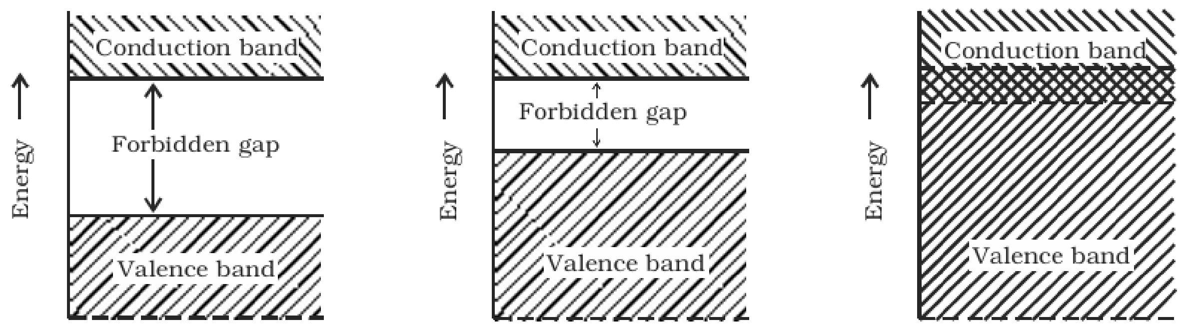
In an insulator, the forbidden energy gap is very large (Fig-a). In general, the forbidden energy gap is more than 3eV and almost no electrons are available for conduction. Therefore, a very large amount of energy must be supplied to a valence electron to enable it to move to the conduction band. In the case of materials like glass, the valence band is completely filled at 0 K. The energy gap between valence band and conduction band is of the order of 10 eV. Even in the presence of high electric field, the electrons cannot move from valence band to conduction band. If the electron is supplied with high energy, it can jump across the forbidden gap. When the temperature is increased, some electrons will move to the conduction band. This is the reason, why certain materials, which are insulators at room temperature become conductors at high temperature. The resistivity of insulator approximately lies between 10^{11} and 10^{16} Ω m.

Semiconductors:

In semiconductors (Fig-b), the forbidden gap is very small. Germanium and silicon are the best examples of semiconductors. The forbidden gap energy is of the order of 0.7eV for Ge and 1.1eV for Si. There are no electrons in the conduction band. The valence band is completely filled at 0K. With a small amount of energy that is supplied, the electrons can easily jump from the valence band to the conduction band. For example, if the temperature is raised, the forbidden gap is decreased and some electrons are liberated into the conduction band. The conductivity of a semiconductor is of the order of 10^2 mho m^{-1}.

Conductors:

In conductors, there is no forbidden gap available, the valence and conduction band overlap each other (Fig-c). The electrons from valence band freely enter into the conduction band. Due to the overlapping of the valence and conduction bands, a very low potential difference can cause the continuous flow of current.



(a) Insulator *(b) Semiconductor* *(c) Conductor*

Fig Energy band of solids

Zener diode:

Zener diode is a reverse biased heavily doped semiconductor (silicon or germanium) PN junction diode, which is operated exclusively in the breakdown region. The symbol of a Zener diode is shown.

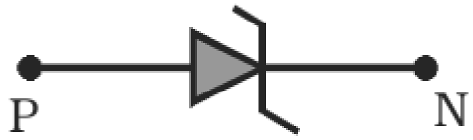


Fig -- Symbol for Zener diode

For normal operation of a Zener diode, in breakdown region, the current through the diode should be limited by an external circuit. Hence the power dissipated across the junction is within its power-handling capacity. Unless this precaution is observed, a large current will destroy the diode.

Characteristics of a Zener Diode:

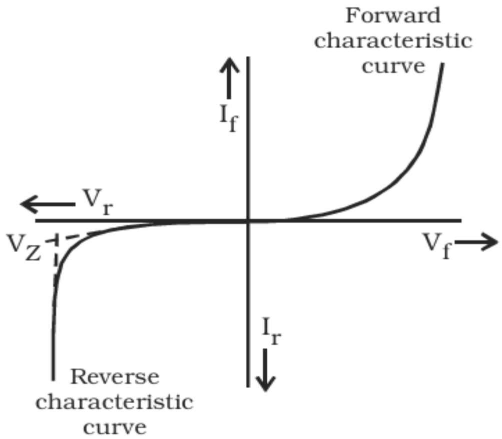


Fig --(b) V - I characteristics of a Zener diode.

The V-I characteristic curve for the Zener diode is shown in Fig (b). The above diagram shows the V-I characteristics of a zener diode. When the diode is connected in forward bias, this diode acts as a normal diode but when the reverse bias voltage is greater than zener voltage, a sharp breakdown takes place. In the V-I characteristics above V_z is the zener voltage. It is also the knee voltage because at this point the current increases very rapidly.

It can be seen from the figure,that, as the reverse voltage applied to the PN junction is increased, at a particular voltage, the current increases enormously from its normal cut off value. This voltage is called zener voltage or breakdown voltage (Vz).

<u>Zener diode as voltage regulator:</u>

To maintain a constant voltage across the load, even if the input voltage or load current varies, voltage regulation is to be made. A Zener diode working in the breakdown region can act as voltage regulator. The circuit in which a Zener diode is used for maintaining a constant voltage across the load RL is shown in Fig (c). The Zener diode in reverse biased condition is connected in parallel with the load RL. Let V_{dc} be the unregulated dc voltage and V_z be Zener voltage (regulated output voltage). Rs is the current limiting resistor. It is chosen in such a way that the diode operates in the breakdown region. Inspite of changes in the load current or in the input voltage, the Zener diode maintains a constant voltage across the load.

Applications and Uses of Zener Diode can be seen in the following:

- As a voltage regulator
- Protects from overvoltage
- Used in clipping circuits
- Used to shift voltage
- Noise reduction

LED (Light Emitting Diode):

A light emitting diode (LED) is a forward biased PN junction diode, which emits visible light when energized.

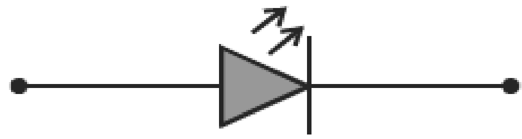
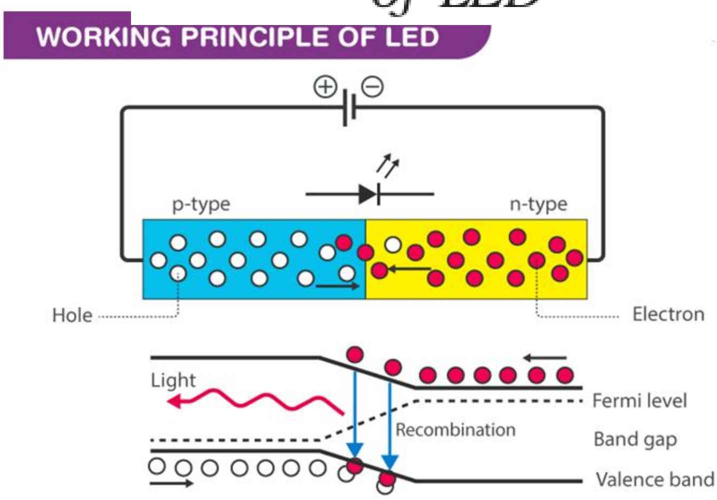


Fig -- Symbol of LED

Construction:

The methods used to construct LED are to deposit three semiconductor layers on the substrate. The three semiconductor layers deposited on the substrate are n-type semiconductor, p-type semiconductor and active region. Active region is present in between the n-type and p-type semiconductor layers. When LED is forward biased, free electrons from n-type semiconductor and holes from p-type semiconductor are pushed towards the active region.

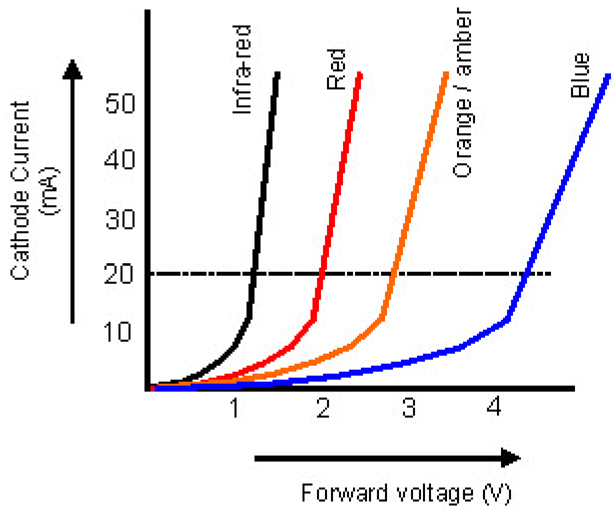


Working: Forward characteristic

When a junction diode is forward biased, electrons from N-side and holes from P-side move towards the depletion region and recombination takes place. When an electron in the conduction band recombines with a hole in the valence band, energy is released. In the case of semiconducting materials like gallium arsenide (GaAs), gallium phosphide (GaP) and gallium – arsenide phosphide (GaAsP), a greater percentage of energy is given out in the form of light. If the semiconductor material is translucent, light is emitted and the junction becomes a light source (turned ON). The LED is turned ON, when it is forward biased and it is turned OFF, when it is reverse biased. The colour of the emitted light will depend upon the type of the material used. By using gallium arsenide phosphide and gallium phosphide, a manufacturer can produce LEDs that radiate red, green, yellow and orange. Fig shows the symbol of LED. LEDs are used for instrument displays, calculators and digital watches.

I-V Characteristics of LED:

There are different types of light-emitting diodes are available in the market and there are different LED characteristics which include the color light, or wavelength radiation, light intensity. The important characteristic of the LED is colour. In the starting use of LED, there is the only red colour. As the use of LED is increased with the help of the semiconductor process and doing the research on the new metals for LED, the different colours were formed.

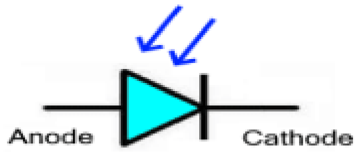


Applications of Light Emitting Diode:

- LED is used as a bulb in the homes and industries
- The light-emitting diodes are used in motorcycles and cars
- These are used in mobile phones to display the message
- At the traffic light signals led's are used
- Used for TV back-lighting
- Used in displays
- Used in Automotives
- LEDs used in the dimming of lights

Photo diode:

- The symbolic representation of Photodiode is shown in fig. A photodiode is a type of a diode that converts light energy into an electrical energy.
- It is a light sensor that generates an electric current when light falls on it.



Photodiode

- The phenomenon through which the light energy is converted into electrical energy is called the photovoltaic effect.
- A solar cell or solar panel consists of an array of photodiodes also called photovoltaic cells that convert solar energy into electrical current.

Construction:

The photodiode is made using two semiconductors like P-type & N-type. It is designed to operate in reverse bias conditions i.e. the P side of the photodiode is connected to the negative while the N side is connected to the positive terminal of the battery. The contacts are designed with metals to make two terminals like anode and cathode. The diode is separated into two types like active & non-active surfaces. The designing of the non-active surface can be done with silicon dioxide (SiO_2). The light rays strike on an active surface whereas, on a non-active surface, the light rays cannot strike. The active surface can be covered through the material of anti-reflection so that the light energy is not lost.

Working of Photodiode: (REVERSE CHARACTERISTICS)

Photodiode works only during the reverse bias. When a photon of energy strikes the diode, it creates electron-hole. This mechanism is also called the inner photoelectric effect. Holes move toward the anode and electrons move toward the cathode, and a photocurrent will be generated. Since it is reversed bias the depletion region is wide. Since the diode is reverse, the reverse saturation current flows. As the intensity of light is increased, the saturation current also increases. Intensity of light is directly proportional to the current.

Power responsivity:

The responsivity of photodiode is a measure of sensitivity to light. It is defined as ratio of photocurrent (Ip) to incident light power P at given wavelength.

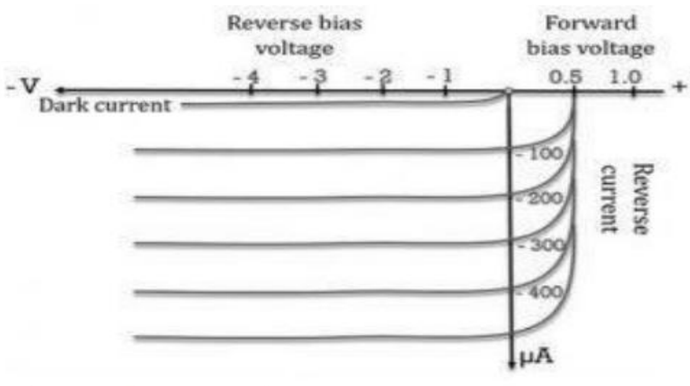
$$Responsivity, R_\lambda = \frac{Ip}{P}$$

In other words, it is measure of the effectiveness of conversion of light power into electric current. It varies with the wavelength of incident light, applied reverse bias and temperature.

V-I Characteristics of Photodiode:

- A photodiode continually operates in a reverse bias mode.
- Photocurrent is independent of reverse bias voltage that is applied.
- For zero luminance, the photocurrent is almost zero excluding for small dark current.
- As optical power rises, the photocurrent also rises linearly.

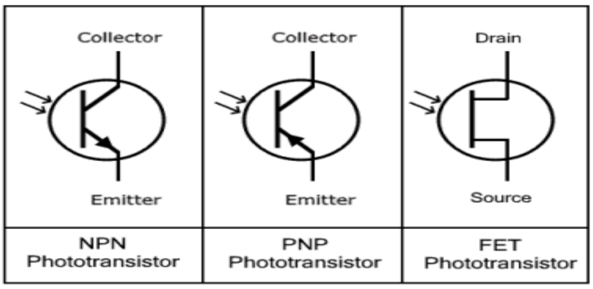
Applications of Photodiode:



- Photodiodes are used for exact measurement of the intensity of light in science industry.
- It is used for detection of both visible as well as invisible light rays.
- Photodiodes are used for the communication system for encoding & demodulation purpose.
- It is also used for digital and logic circuits which require fast switching and high-speed operation.
- They are used for lighting regulation and in optical communications.

Phototransistor:

Symbol of Phototransistor



Phototransistor is a light-controlled switch that switches a circuit and amplifies the current when exposed to light.

Construction:

The construction of a phototransistor is similar to any normal transistor except for the missing base terminal and the wide light-sensitive base region. Commonly bipolar Phototransistor is used. Unlike a normal transistor, a phototransistor has only two terminals, an emitter and collector.

The symbol of the phototransistor is very similar to any normal transistor except for the base terminal. Instead of the base terminal, there are two pointing arrows representing incident light as shown in the figure below. In an NPN phototransistor, the emitter terminal has an arrow pointing outward while PNP has an emitter pointing inward. For identification, the collector is longer than the emitter and the emitter has a flat spot at the top.

Working:

- Phototransistor operates just like any normal bipolar transistor except for the fact that the base current is generated by a light source instead of a voltage source.
- The base current is generated on the principle of the photovoltaic effect. According to this phenomenon when photons strike the PN junction, electron-hole pairs are generated that separate and move in the opposite direction thus creating a base current.
- The base current is then amplified by the transistor action. Therefore, the Phototransistor is 100 times more sensitive than the photodiode.
- When biasing, the collector is kept at a higher voltage with respect to the emitter in NPN phototransistor and the collector to the base junction is reverse biased.

- The base terminal is kept open or not connected otherwise it will operate as a normal transistor.
- Under no light conditions, there is a small reverse saturation current or leakage current called dark current that is directly proportional to the temperature as in photodiodes.
- When light shines on the phototransistor, the lens focuses the light onto the collector-base junction and generates a base current due to the photovoltaic effect. The base current is amplified.

Applications:

Light sensing: They are widely used to detect light and measure the intensity of light.

Automatic light control:

It can automatically control the light in street or on the highway. It senses the sunrise and sunset and switches on or off the connected lights on the circuit.

Object counter:

It senses an object when it passes between it and a constant light source. It triggers the connected circuit when the object interrupts the incident light.

Opto-coupler:

It electrically isolates two circuits and optically connects them using light pulses to protect low voltage circuits from high voltage circuits.

Punch card reader: Used in punch card readers.

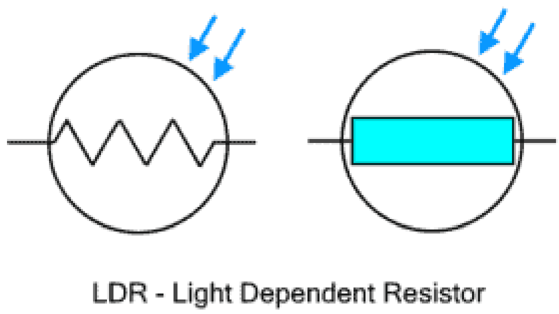
Shutter control: Controls the opening of the camera shutter based on the intensity of the light falling on its lens.

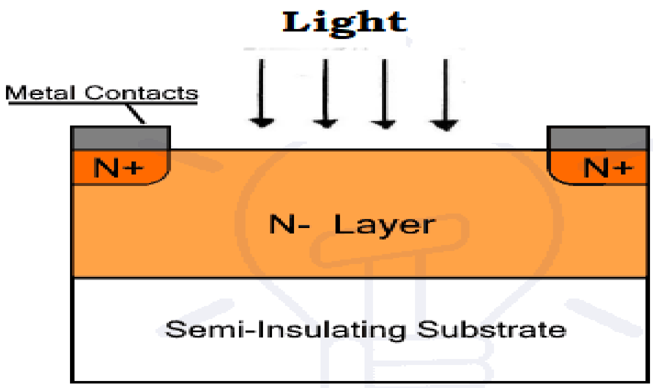
Alarms: Used in burglar alarms by detecting the presence of a person passing through it. Fire alarm and smoke alarm also uses phototransistor.

Light Dependent Resistor-(LDR)

A Light Dependent Resistor (LDR) or a photo resistor is a device whose resistivity is a function of the incident electromagnetic radiation. Hence, they are light sensitive devices. They are also called as photo conductors, photo-conductive cells or simply photocells. They are made up of semiconductor materials having high resistance. There are many different symbols used to indicate a LDR, one of the most commonly used symbol is shown in the figure below. The arrow indicates light falling on it.

Fig:Symbol of LDR





LDR Structure

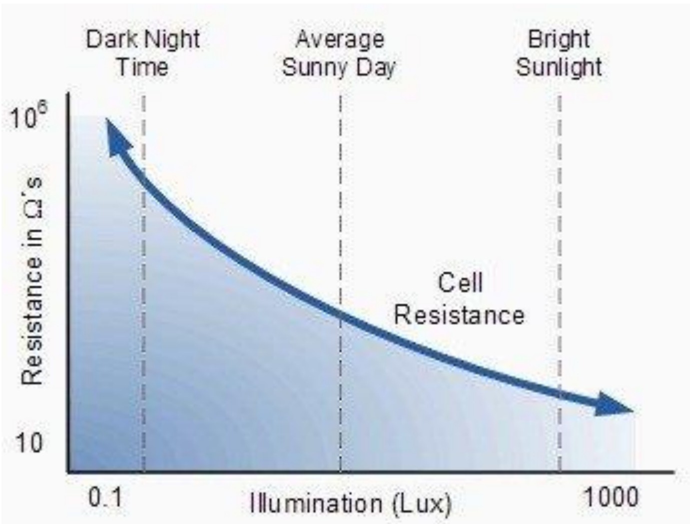
Working Principle of LDR:

A light dependent resistor works on the principle of photoconductivity. Photoconductivity is an optical phenomenon in which the materials conductivity is increased when light is absorbed by the material.

When light falls i.e. when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in large number of charge carriers. The result of this process is more and more current starts flowing through the device when the circuit is closed and hence it is said that the resistance of the device has been decreased. This is the most common working principle of LDR.

Characteristics of LDR:

LDR's are light dependent devices whose resistance is decreased when light falls on them and that is increased in the dark. When a light dependent resistor is kept in dark, its resistance is very high. This resistance is called as dark resistance. It can be as high as 1012 Ω and if the device is allowed to absorb light its resistance will be decreased drastically. If a constant voltage is applied to it and intensity of light is increased the current starts increasing. Figure below shows resistance vs. illumination curve for a particular LDR.



Photocells or LDR's are non linear devices. There sensitivity varies with the wavelength of light incident on them. Some photocells might not at all response to a certain range of wavelengths. Based on the material used different cells have different spectral response curves.

When light is incident on a photocell it usually takes about 8 to 12 ms for the change in resistance to take place, while it takes one or more seconds for the resistance to rise back again to its initial value after removal of light. This phenomenon is called as resistance recovery rate. This property is used in audio compressors. Also, LDR's are less sensitive than photo diodes and phototransistor. (A photo diode and a photocell (LDR) are not the same, a photo-diode is a pn junction semiconductor device that converts light to electricity, whereas a photocell is a passive device, there is no pn junction in this nor it "converts" light to electricity).

Applications of LDR

1. Light sensors,
2. Camera light meter,
3. Street lamps, Alarm clock,
4. Burglar alarm circuits,
5. Light intensity meters,

6. Counting the packages moving on a conveyor belt.

Resistance Temperature Detector:

An RTD or resistance thermometer stands for resistance temperature detector that is used for measuring the change in temperature by measuring the variation in resistance over the temperature range. It can be described as a temperature transducer that converts heat energy into some other form of energy.

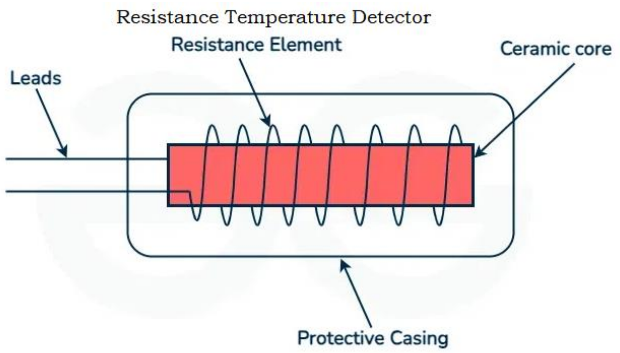
Resistance temperature detectors are usually detectors of wire resistance temperature that are made up of platinum, nickel, or resistance wire elements. The flexibility of choosing their configuration and shape makes them an easy-to-use device. It shows good linear characteristics over a range of temperatures which makes it predictable and useful. There are some other transducers as well like a thermocouple or a thermistor. Each can be used depending on the need.

Construction of Resistance Temperature Detector:

The construction of RTD involves wrapping the resistance wire on mica base. The wire is wrapped in a way to minimize the inductance between each turn of the coil. The whole coil is encased by a stainless steel case in order to protect the wiring. The ending of the wire terminate into leads. Usually the material that are employed to make RTDs should have positive temperature coefficient meaning their resistance should rise with increase in temperature. This means that metals that show linear characteristics should be used some of these materials are ***Copper, Nickel and Platinum.***

Working:

As we can see that RTD consist of a resistance elements which is fragile and therefore needs a protection which is done by providing insulation as shown by the protection tube. The insulated tube is connected to the element. Usually a metal alloy is used as protective tube because of its chemically inert behaviour.



The temperature begins from 00 C and can vary up-to the temperature range where metal shows linear change in characteristics. This range is dependant on the type of metal or resistance element being used like the range is till 650°C for platinum and can be around 300°C for nickel.

$$\alpha = \frac{R_{100} - R_0}{100° \times R_0}$$

Where, $R_0 - resistance\ of\ the\ sensor\ at\ temperature\ 0°C$

$R_{100} - resistance\ of\ the\ sensor\ at\ temperature\ 100°C$

This is how we can predict the temperature of device by using the linear nature of resistance element. Note that the electric current through the RTD resistance must be kept sufficiently low and constant to avoid self-heating. and also the temperature coefficient will differ from metal to metal.

Applications of an RTD:

Let us now some applications of RTDs

- Automotive industry uses RTDs largely for measuring the temperature change in case of engines and oil level sensors to ensure accurate functioning of these devices.
- Food processing industry uses RTDs for the purpose of temperature change in various food processing devices like containers and instruments.
- RTDs also find their application in electronics industry where they are used for sensing the temperature range of various amplifiers, transistors and stabilizers to ensure that they don't exceed the limit and burn-out.
- RTDs are also used in medical industry where it is used in medical surgical devices for measuring temperature of heated surgical trays to ensure accurate temperature is set.
- Other places that use RTDs are power electronics industry, computer industry, consumer electronics, food handling industry and even military and aerospace.

SENSOR MECHANISM:

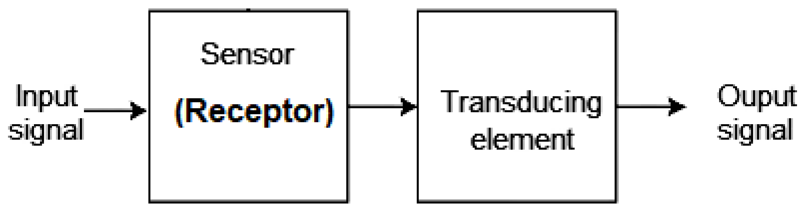
A sensor's sensing mechanism is the process of detecting a physical change in the environment and converting it into a measurable signal, typically electrical. This involves a receptor to detect the input (like light, temperature, or a chemical), a transduction stage to convert this input into an electrical signal, and a display or processor to interpret and output the data.

For specific examples, the sensing mechanism in a metal oxide gas sensor involves gas molecules extracting electrons from the material's surface, altering its conductivity, while electrochemical sensors use a membrane that is selective to a particular ion to create a voltage at equilibrium.

General Sensing mechanism

Receptor:

A part of the sensor that detects the physical input from the environment, such as light, temperature, pressure, or motion.



Sensor Mechanism

Transduction:

The process where the detected physical input is converted into another form of energy, most commonly an electrical signal (voltage or current).

Output:

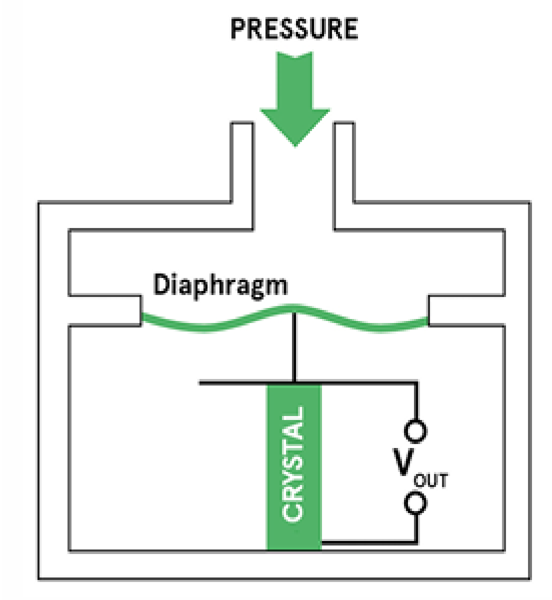
The electrical signal is then transmitted to a display, a processing unit, or another electronic device for monitoring, analysis, or further action.

Piezoelectric effect: Definition:

The piezoelectric effect is the ability of certain materials, like crystals and ceramics, to generate an electric charge when mechanical stress is applied to them.

Piezoelectric sensor:

A piezoelectric sensor is a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge.



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

Piezoelectric pressure sensors exploit this effect by measuring the voltage across a piezoelectric element generated by the applied pressure. They are very robust and are used in a wide range of industrial applications.

Construction:

The piezoelectric effect requires materials with a specific asymmetry in the crystal structure. This includes some natural crystals, such as quartz or tourmaline.

In addition, specially formulated ceramics can be created with a suitable polarisation to make them piezoelectric. These ceramics have higher sensitivities than natural crystals. A useful output can be generated with as little as 0.1% deformation.

Because the piezoelectric materials are rigid, only a very small deflection of the material is required to get a usable output signal. This makes the sensors very robust and tolerant of over-pressure conditions. It also means they respond rapidly to changes in pressure.

The pressure sensor can be affected by any external force on the piezoelectric element, for example, by forces caused by acceleration or noise.

Micro sensors can be constructed using thin films. Zinc oxide was one of the first materials used. This has largely been replaced by ceramics made from materials such as lead zirconate titanate (PZT) because of their larger piezoelectric effect.

Microelectromechanical systems (MEMS) can be created by combining piezoelectric thin films with micro machined silicon membranes.

Piezoelectric materials are also used in some other types of MEMS sensors. For example, the inverse piezoelectric effect is used to generate surface acoustic waves through a diaphragm. The distortion of the surface under pressure can then be detected by the changes it causes in the waves that are received by another piezoelectric element.

Design:

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

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

This can cause changes to the output due to heating of the crystal, the diaphragm or the casing of the sensor. Note that this is not the same as the static temperature sensitivity of the sensor.

The effects of thermal shock can be minimised by the design of the enclosure and mounting the sensor to provide isolation.

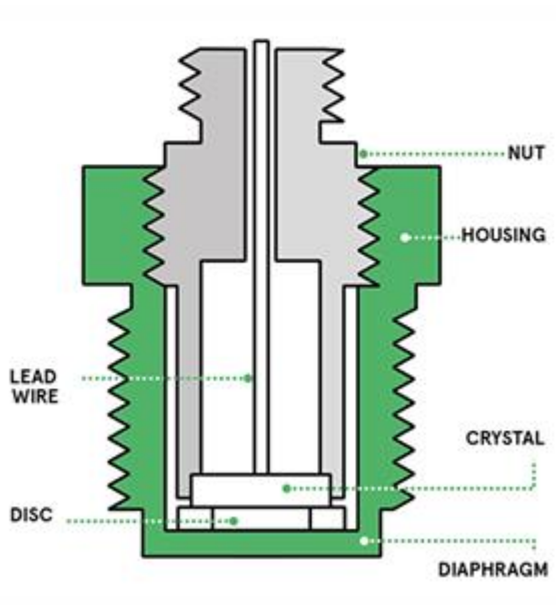
Working principle:

When a force is applied to a piezoelectric material, an electric charge is generated across the faces of the crystal. This can be measured as a voltage proportional to the pressure (see diagram to the right).

There is also an inverse piezoelectric effect where applying a voltage to the material will cause it to change shape.

A given static force results in a corresponding charge across the sensor. However, this will leak away over time due to imperfect insulation, the internal sensor resistance, the attached electronics, etc.

As a result, piezoelectric sensors are not normally suitable for measuring static pressure. The output signal will gradually drop to zero, even in the presence of constant pressure. They are, however, sensitive to dynamic changes in pressure across a wide range of frequencies and pressures.



This dynamic sensitivity means they are good at measuring small changes in pressure, even in a very high-pressure environment.

Applications

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

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

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

Advantages and disadvantages:

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

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

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

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

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

Metal oxide semiconductor sensor:

What is semiconductor gas sensors?

Semiconductor-based gas sensors, also known as **MOS (Metal Oxide Semiconductor) sensors.** A Semiconductor Gas Sensor detects gas concentration based on changes in the electrical resistance of a metal oxide semiconductor material, typically tin dioxide (SnO_2) or zinc oxide (ZnO), when exposed to a target gas.

They are also referred to as:

- MOS gas sensors
- Chemo resistive gas sensors
- Metal oxide sensors

These sensors are highly effective for detecting reducing gases like CO, H_2, CH_4, and alcohol vapours.

Metal Oxide Semiconductor (MOS) gas sensors work by detecting changes in electrical resistance due to gas molecules interacting with the sensor's metal oxide material. In clean air, the heated metal oxide surface adsorbs oxygen, which traps electrons and increases the material's resistance. When a target gas, like carbon monoxide, is present, it reacts with the adsorbed oxygen, releasing the trapped electrons and causing the sensor's resistance to decrease. The sensor measures this change in resistance to determine the concentration of the gas.

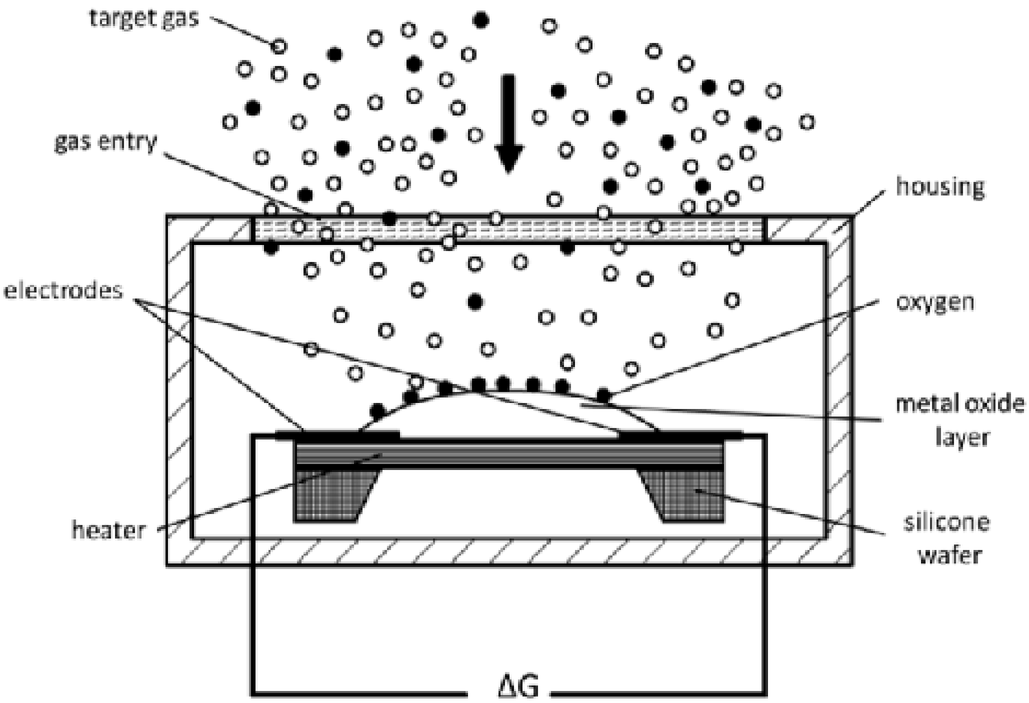
Principle:

When semiconductor particles (typically tin dioxide) are heated in air at high temperature, oxygen is adsorbed on the particle surface by capturing free electrons. The depletion layer thus formed is largely dependent on the radius of semiconductor particles used. If it is as small as conventionally used in gas sensors (tens nano-meters), the depletion can extend up to the whole area of each particle (volume depletion, high sensitive). If the size is far larger, on the other hand, depletion takes place conventionally on the periphery of each particle (regional depletion, low sensitive).

The principle of a metal oxide gas sensor relies on the change in electrical resistance of a metal oxide semiconductor when it interacts with gas molecules. In the presence of air, oxygen molecules adsorb onto the surface of the heated metal oxide, trapping electrons and creating a depletion layer that increases its electrical resistance. When a target gas (e.g., a reducing gas like H_2 or CO) is introduced, it reacts with these surface oxygen species, releasing the trapped electrons back into the metal oxide, which decreases the sensor's resistance.

Construction:

A base material, often a ceramic (like zirconia) or a silicon wafer, provides the structural support for the sensor. A resistive heating element, often made of platinum, is integrated onto the substrate to raise the metal oxide-sensing layer to its optimal operating temperature. Two interdigitated electrodes are patterned on the substrate. These are made of a conductive material and are crucial for measuring the electrical resistance of the sensing layer, as they are in direct contact with it. The porous sensing layer is deposited on top of the electrodes and heater. The layer is composed of a metal oxide semiconductor, such as SNO_2, ZnO, Fe_2O_3 ETC…



Working:

Oxygen from the air adsorbs onto the surface of the metal oxide grains, capturing electrons and creating a "depletion layer" that increases the material's resistance. When a target gas (e.g., a reducing gas) is present, it reacts with the adsorbed oxygen, releasing the captured electrons back into the metal oxide. This release of electrons reduces the depletion layer and decreases the sensor's resistance. The magnitude of this resistance change is directly related to the concentration of the gas being detected.

It is designed to have a porous structure made of many small grains to maximize the surface area for gas interaction. The layer can be applied using various methods, such as drop casting, screen-printing, or vapour transport, to form the desired porous film.

HALL SENSORS:

Edwin Hall discovers Hall voltage in 1879. Hall Effect is caused due to the nature of current in a conductor. Many inventions used this Hall Effect theory. This theory is also used in current sensors, pressure sensors, Fluid flow sensors etc... One such invention that can measure magnetic field is the Hall Effect sensor.

Definition:

A Hall effect sensor works by using the Hall effect principle: when a current-carrying conductor is exposed to a perpendicular magnetic field, a voltage difference (called Hall voltage) is generated across the conductor, perpendicular to both the current and the magnetic field. This voltage is proportional to the magnetic field strength and can be used to detect the presence, strength, or direction of a magnetic field.

Hall Effect Sensor Definition:

Hall-effect sensors are the linear transducers that are used to measure the magnitude of the magnetic field. Working on the principle of Hall Effect, these sensors generate a Hall voltage when a magnetic field is detected, which is used to measure the magnetic flux density.

Linear sensors can measure the wide range of magnetic fields. Besides magnetic fields, these sensors are also used for detecting proximity, position, speed. For these sensors output voltage is directly proportional to the magnitude of the magnetic field.

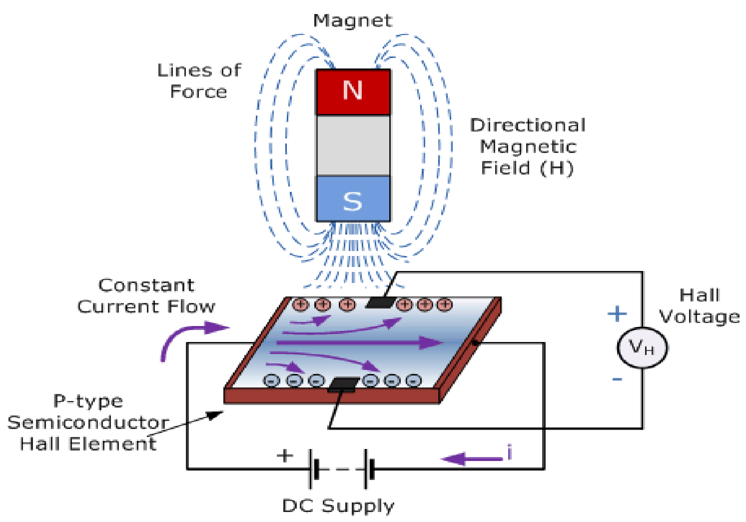
Construction:

Hall Effect Sensors consist of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), indium antimonide (InSb) or indium arsenide (InAs) passing a continuous current through itself.

When the device is placed within a magnetic field, the magnetic flux lines exert a force on the semiconductor material which deflects the charge carriers, electrons and holes, to either side of the semiconductor slab.

This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material.

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



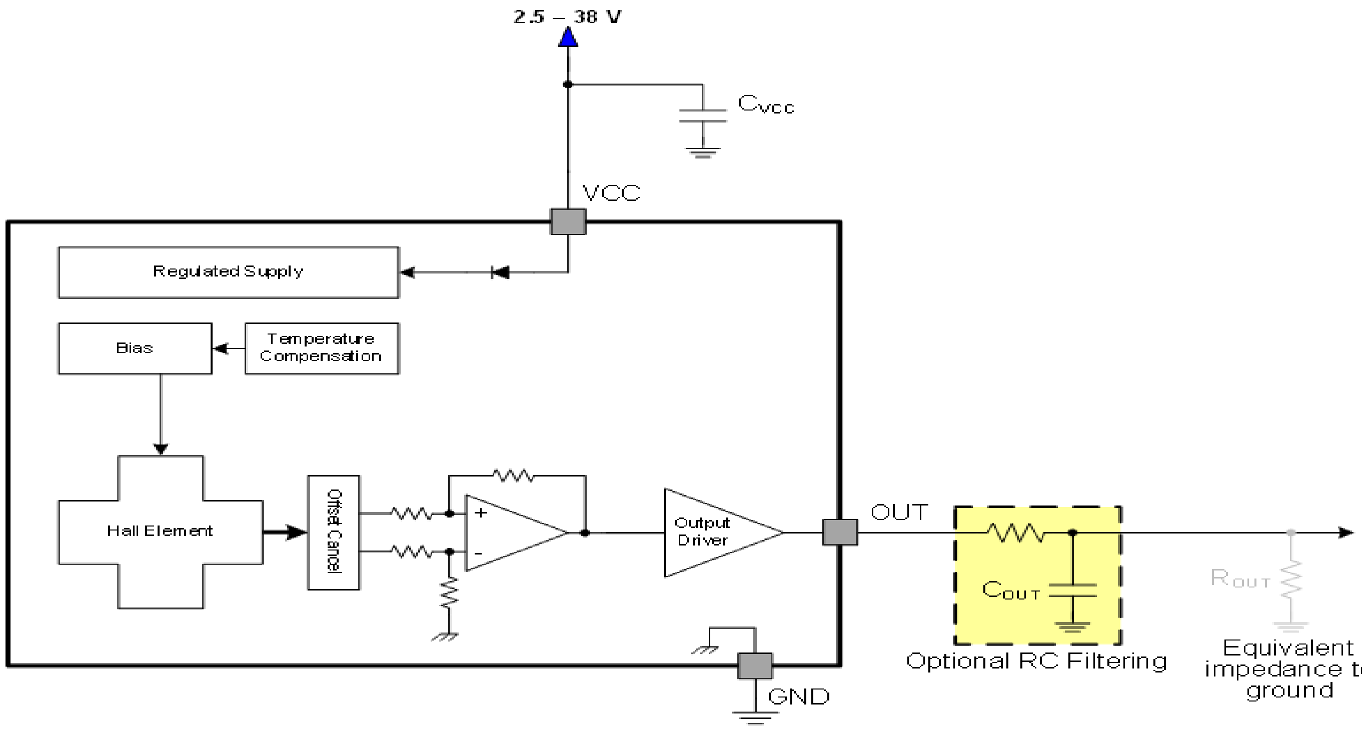
Working Principle of Hall Effect Sensor:

The principle of Hall voltage is used as a working principle of the Hall Effect sensor. On a thin strip of a conductor, electrons flow in a straight line when electricity is applied.

When this charged conductor comes in contact with the magnetic field which is in a perpendicular direction to the motion of electrons, the electrons get deflected.

Some electrons get collected on one side while some on another side. Due to this, one of the conductor's plane behaves as negatively charged while the other behaves as positively charged. This creates potential difference and voltage is generated. This voltage is called the Hall voltage.

The electrons continue to move from one side of the plane to other till a balance is achieved between the force applied on charged particles due to an electric field and the force that caused magnetic flux that caused this change. When this separation stops, the hall voltage value at that instant gives the measure of magnetic flux density.



Applications of Hall Effect Sensor:

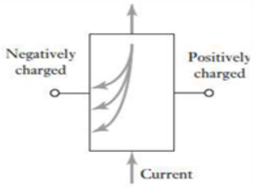
The applications of Hall-effect sensors are as follows:

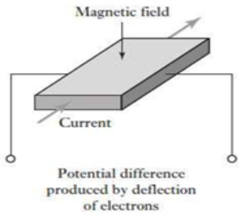
- When combined with threshold detection they act as a switch.
- These are used in ultra-high-reliability applications such as keyboards.
- Hall Effect sensors are used to time the speed of wheels and shafts.
- These are used to detect the position of permanent magnet in brushless electric DC motors.
- Hall Effect sensors are embedded in digital electronic devices along with linear transducers.
- Sensing the presence of the magnetic field in industrial applications.
- Used in smartphone to check whether the flip cover accessory is closed.
- For contactless measurement of DC current in current transformers, Hall Effect sensor is used.

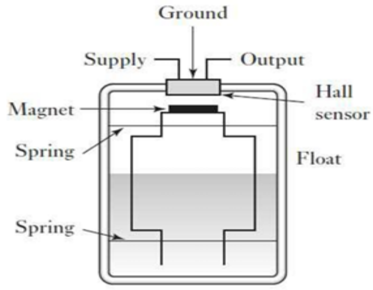
- This is used as a sensor to detect the fuel levels in automobiles.

Hall Effect Sensors

- A Hall effect sensor is a device that is used to measure the magnitude of a magnetic field.
- Its output voltage is directly proportional to the magnetic field strength through it.
- Hall effect sensors are used for proximity sensing, positioning, speed detection, and current sensing applications.
- When a beam of charged particles passes through a magnetic field, forces act on the particles and the beam is deflected from its straight line path.







NUMERICALS – MODULE 5 - Electronic Devices and Sensors

TEMPERATURE COEFFICIENT:

1. The resistance of a bulb filament is 112Ω at a temperature of 110°C. and its resistance is 180Ω at 375 °C. Calculate its temperate coefficient.

$$\mathbf{R_T = R_0\,[(1 + \alpha\,(T - T_0)]}$$

$$112 = R_0[(1 + \alpha\ X100)] - -(1)$$

$$180 = R_0[(1 + \alpha\ X\,375\,)] - - - (2)$$

$$\frac{180}{112} = \frac{R_0[(1 + \alpha\ X\,375\,)]}{R_0[(1 + \alpha\ X100)]}$$

$$1.6 = \frac{(1 + 375\,\alpha)}{(1 + 100\,\alpha)}$$

$$1.6 + 160\,\alpha = 1 + 375\,\alpha$$

$$215\,\alpha = 0.6$$

$$\alpha = 0.00279\ Per°C$$

2. The resistance of a bulb filament is 100Ω at a temperature of 100°C. If its TCR is 0.005 per °C, its resistance will become 200Ω at a temperature of?

$$\mathbf{R_T = R_0\,[(1 + \alpha\,(T - T_0)]}$$

$$100 = R_0(1 + 0.005\ X100)] - -(1)$$

$$200 = R_0(1 + 0.005\ X\,T\,)] - - - (2)$$

$$\frac{200}{100} = \frac{R_0[(1 + 0.005\ X\,T\,)]}{R_0[(1 + 0.005\ X100)]}$$

$$2 = \frac{(1 + 0.005T)}{1.5}$$

$$1 + 0.005T = 3$$

$$T = \frac{2}{0.005}$$

$$T = 400°C$$

3. The resistance of a wire is 5Ω at 50°C and 6Ω at 100°C. Then what will be the resistance of the wire at 0°C?

Solution:

We know that $R_T = R_0 [1+ \alpha (T-T_0)]$

$5 = R_0 [1+50\alpha]$.........(1)

$6 = R_0 [1+100\alpha]$........(2)

Dividing Equations (1) and (2)

$5/6 = 1+50\alpha/1+100\alpha$

$\alpha = 1/200$

From (1)

$5 = R_0 [1+50(1/200)]$

$R_0 = 4\Omega$

4. The resistance of a bulb filament is 100Ω at a temperature of 100°C. If its temperature coefficient of resistance is 0.005 per °C, its resistance will become 200Ω at a temperature of ____.

Solution:

As we know that $R_T = R_0 [1+ \alpha (T-T_0)]$

$100 = R_0 [1+ 0.005\times100]$

And $200 = R_0 [1+ 0.005x\ T]$

Here, T is the temperature in °C at which the resistance becomes 200Ω.

$200/100 = (1+ 0.005x\ T)/(1+ 0.005\times100)$

$T = 400°C$

5. A platinum resistance thermometer has a resistance $R_0 = 40.0\ \Omega$ at T_0=30 °C. α for Pt is $3.92\times10^{-3}(°C)^{-1}$. The thermometer is immersed in a vessel containing melting tin, at which point R increases to 94.6Ω. What is the melting point of tin?

Given:

$R_0 = 40.0\ \Omega$, $R_T = 94.6\Omega$

$T_0 = 30\ °C$, $T = ?$

Solution:

$R_T = R_0\,[1 + \alpha\,(T - T_0)]$

$94.6\Omega = 40\Omega\,[1 + 3.92 \times 10^{-3}\,(°C)^{-1}\,(T - 30°C)]$

$2.365 = [1 + 3.92 \times 10^{-3}\,(°C)^{-1}\,(T - 30°C)]$

$1.365 = 3.92 \times 10^{-3}\,(°C)^{-1}\,(T - 30°C)$

$211°C = T - 30°C$

$\mathbf{T = 241\ °C}$

The melting point of tin is 241^0C.

<u>NUMERICALS ON PHOTODIODE</u>

Photodiode Responsivity Formula

The following formula is used to calculate Photodiode Responsivity:

Photodiode Responsivity:-

$$R_\lambda = \frac{I_p}{P} \text{ (A/W)}$$

Since $h\upsilon$ = energy of photon, $P = r_p\,h\upsilon$

where r_p = photon flux $= P/h\upsilon = \#$ photons/ sec

Photodiode responsivity (R_λ) is a measure of a photodiode's efficiency in converting incident optical power into electrical current. It is defined as the ratio of the generated photocurrent (I_p) to the incident optical power (P) at a given wavelength (λ).

The key formulas used in photodiode responsivity calculations are:

- **Responsivity (R_λ):**
  $$R_\lambda = \frac{I_p}{P}$$
- **Relationship between responsivity (R_λ) and quantum efficiency (η):**
  $$R_\lambda = \frac{\eta q \lambda}{hc}$$
  where:
  - η = Quantum efficiency (the fraction of incident photons producing an electron-hole pair).
  - q = Elementary charge (1.602×10^{-19} C).
  - λ = Wavelength of the incident light.
  - h = Planck's constant (6.626×10^{-34} J·s).
  - c = Speed of light (3×10^{8} m/s).

Example 1: Calculating photocurrent from responsivity

A p-i-n photodiode has a responsivity of 0.8 A/W at a given wavelength. If $10\ \mu$W of optical power is incident on the photodiode, what is the generated photocurrent?

Solution:

1. **Identify the given values:**
   1. Responsivity, $R_\lambda = 0.8$ A/W
   2. Incident optical power, $P = 10\ \mu\text{W} = 10 \times 10^{-6}$ W
2. **Use the responsivity formula to find the photocurrent:**
   1. $R_\lambda = \frac{I_p}{P}$
   2. $I_p = R_\lambda \times P$
   3. $I_p = (0.8 \text{ A/W}) \times (10 \times 10^{-6} \text{ W}) = 8 \times 10^{-6}$ A
3. **State the answer:**
   1. The generated photocurrent is $8\ \mu$A.

Example 2: Calculating responsivity

A photodiode generates a photocurrent of $10\ \mu\text{A}$ when illuminated with a light source of $20\ \mu\text{W}$. Calculate the responsivity of the photodiode.

Solution:

1. **Identify the given values:**
   1. Photocurrent, $I_p = 10\ \mu\text{A} = 10 \times 10^{-6}\ \text{A}$
   2. Incident optical power, $P = 20\ \mu\text{W} = 20 \times 10^{-6}\ \text{W}$
2. **Use the responsivity formula:**
   1. $R_\lambda = \dfrac{I_p}{P}$
   2. $R_\lambda = \dfrac{10 \times 10^{-6}\ \text{A}}{20 \times 10^{-6}\ \text{W}} = 0.5\ \text{A/W}$
3. **State the answer:**
   1. The responsivity is $0.5\ \text{A/W}$.

Example 3: Calculating responsivity from quantum efficiency

A photodiode has a quantum efficiency of 75% at a wavelength of 900 nm. Calculate the responsivity.

Solution:

1. **Identify the given values:**
   1. Quantum efficiency, $\eta = 75\% = 0.75$
   2. Wavelength, $\lambda = 900\ \text{nm}$
2. **Use the simplified responsivity formula ($R_\lambda = \dfrac{\eta\lambda}{1240}$):**
   1. $R_\lambda = \dfrac{(0.75) \times (900)}{1240} \approx 0.544\ \text{A/W}$
3. **State the answer:**
   1. The responsivity is approximately $0.544\ \text{A/W}$.

Example 4: Calculating incident optical power

A photodiode with a quantum efficiency of 80% generates a photocurrent of $5\ \mu\text{A}$ when illuminated with light of wavelength 550 nm. Calculate the incident optical power.

Solution:

1. **Identify the given values:**
   1. Quantum efficiency, $\eta = 80\% = 0.80$
   2. Photocurrent, $I_p = 5\ \mu\text{A} = 5 \times 10^{-6}\ \text{A}$
   3. Wavelength, $\lambda = 550\ \text{nm}$
2. **First, calculate the responsivity (R_λ) using the simplified formula:**
   1. $R_\lambda = \dfrac{\eta\lambda}{1240}$
   2. $R_\lambda = \dfrac{(0.80) \times (550)}{1240} \approx 0.355\ \text{A/W}$
3. **Next, use the responsivity to find the incident optical power (P):**
   1. $P = \dfrac{I_p}{R_\lambda}$
   2. $P = \dfrac{5 \times 10^{-6}\ \text{A}}{0.355\ \text{A/W}} \approx 1.408 \times 10^{-5}\ \text{W}$
4. **State the answer:**
   1. The incident optical power is approximately $14.08\ \mu\text{W}$.

The Hall sensor's voltage sensitivity (S_V) is defined as the Hall voltage (V_H) per unit of magnetic flux density (B) for a given bias current. The provided formula, $S_V = R_H/d$, relates the sensitivity to the Hall coefficient (R_H) and the thickness (d) of the conductive material.

Key formulas

- **Hall voltage (V_H):** The voltage generated across the sensor is given by:
  $V_H = \frac{R_H \cdot I \cdot B}{d}$
  - I = Bias current
  - B = Magnetic flux density
  - d = Thickness of the Hall element
  - R_H = Hall coefficient, dependent on the material and carrier concentration
- **Voltage sensitivity (S_V):** This is derived from the Hall voltage equation as the change in voltage per change in magnetic field ($S_V = V_H/B$):
  $S_V = \frac{R_H \cdot I}{d}$
- **Material-dependent sensitivity (S_{VI}):** Sensitivity is sometimes also expressed per unit of bias current ($S_{VI} = V_H/(I \cdot B)$), which simplifies to:
  $S_{VI} = \frac{R_H}{d}$

<u>NUMERICALS ON HALL SENSORS:</u>

Problem

A Hall sensor is made from a semiconductor with a Hall coefficient (R_H) of $3.66 \times 10^{-4}\ \mathrm{m^3/C}$. The sensor has a thickness (d) of 0.5 mm and is operated with a constant bias current (I) of 5.1 mA.

1. Calculate the voltage sensitivity (S_V) of the sensor.
2. If the sensor is placed in a magnetic field with a flux density (B) of 500 G, what will the Hall voltage (V_H) be?

Solution

1. Calculate the voltage sensitivity (S_V).
First, convert the given values to standard SI units:

- $R_H = 3.66 \times 10^{-4}\ \mathrm{m^3/C}$
- $I = 5.1\ \mathrm{mA} = 5.1 \times 10^{-3}\ \mathrm{A}$
- $d = 0.5\ \mathrm{mm} = 0.5 \times 10^{-3}\ \mathrm{m}$

Using the formula for voltage sensitivity:

$$S_V = \frac{R_H \cdot I}{d}$$

$$S_V = \frac{(3.66 \times 10^{-4}\ \mathrm{m^3/C}) \cdot (5.1 \times 10^{-3}\ \mathrm{A})}{0.5 \times 10^{-3}\ \mathrm{m}}$$

$$S_V = \frac{1.8666 \times 10^{-6}}{0.5 \times 10^{-3}}\ \mathrm{V/T}$$

$$S_V = 3.7332 \times 10^{-3}\ \mathrm{V/T}$$

The voltage sensitivity of the Hall sensor is 3.73×10^{-3} V/T, or 3.73 mV/T.

2. Calculate the Hall voltage (V_H).

First, convert the magnetic flux density from Gauss to Tesla:

- $1\ \mathrm{G} = 1 \times 10^{-4}\ \mathrm{T}$
- $B = 500\ \mathrm{G} = 500 \times 10^{-4}\ \mathrm{T} = 0.05\ \mathrm{T}$

Using the Hall voltage formula ($V_H = S_V \cdot B$):

$$V_H = (3.7332 \times 10^{-3}\ \mathrm{V/T}) \cdot (0.05\ \mathrm{T})$$

$$V_H = 0.18666 \times 10^{-3}\ \mathrm{V}$$

$$V_H = 0.187\ \mathrm{mV}$$

Alternatively, use the full Hall voltage equation:

$$V_H = \frac{R_H \cdot I \cdot B}{d}$$

$$V_H = \frac{(3.66 \times 10^{-4}) \cdot (5.1 \times 10^{-3}) \cdot (0.05)}{0.5 \times 10^{-3}}\ \mathrm{V}$$

$$V_H = 0.187\ \mathrm{mV}$$

The Hall voltage produced by the sensor is **0.187 mV**.