PHYSICS

SEMICONDUCTOR DEVICES

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Introduction:

Most of the solids can be placed in one of the two classes: Metals and insulators. Metals are those through which electric charge can easily flow, while insulators are those through which electric charge is difficult to flow. This distinction between the metals and the insulators can be explained on the basis of the number of free electrons in them. Metals have a large number of free electrons which act as charge carriers, while insulators have practically no free electrons.

There are however, certain solids whose electrical conductivity is intermediate between metals insulators. They Semiconductors". and are called Carbon, silicon and germanium are examples of semi-conductors. In semiconductors the outer most electrons are neither so rigidly bound with the atom as in an insulator, nor so loosely bound as in metal.

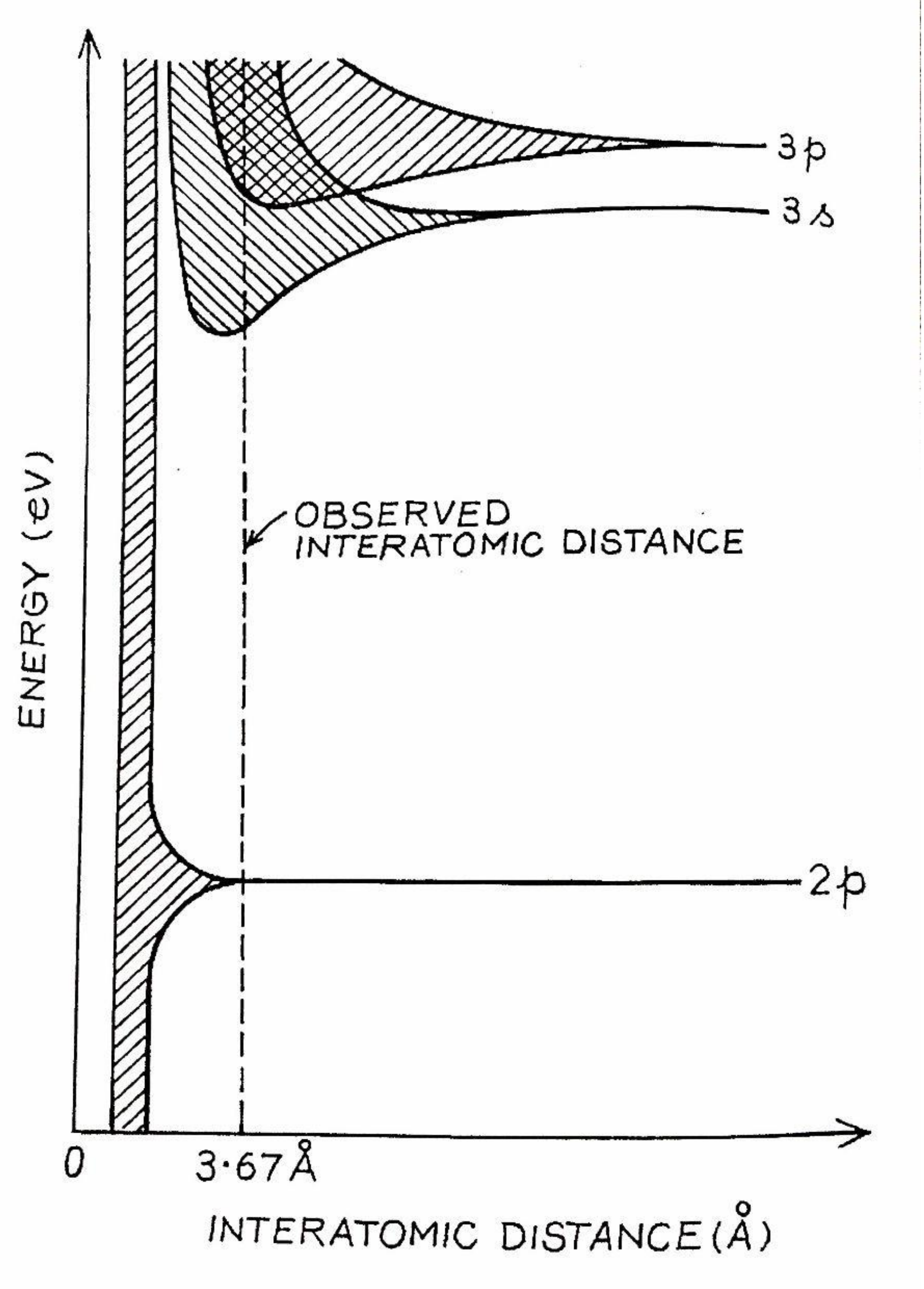
At absolute zero a semiconductor becomes an ideal insulator

Energy Band in Materials:

A material contains an enormous number of atoms packed closely together. Each atom, when isolated, has a discrete set of electron energy levels named as 1s, 2s, 2p. 3s, 3p, ... If we imagine all the N (say) atoms of the material to be isolated from one another, then they would have completely coinciding sets of energy levels. That is, each of the energy levels of this N-atom system would have an N-fold degeneracy. The electrons fill the energy levels in each atom independently. As the atoms approach one another to form the material, a continuously increasing interaction occurs between them which causes each of the levels to "split" into N distinct levels. In practice, however, N is very large (103/cm). Therefore, the split energy levels become so numerous and so close together that they form an almost continuous "energy band".

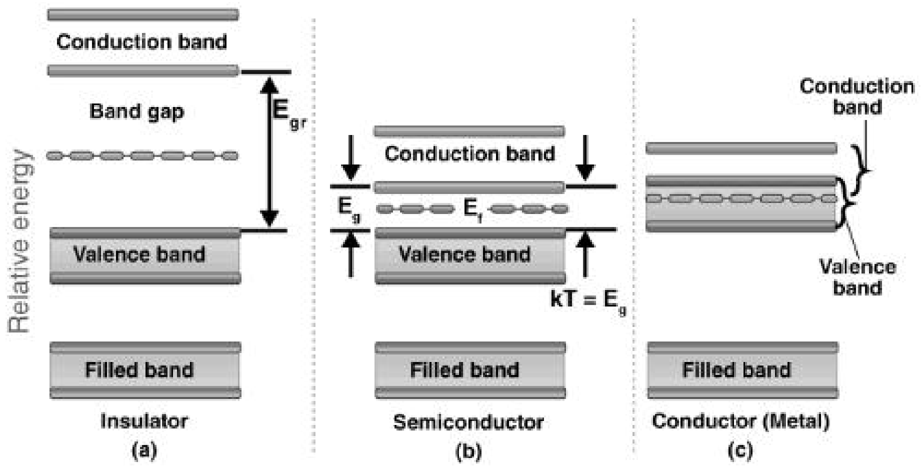
The amount of splitting is different for different energy levels. In general, the lower levels are split less than the higher levels, the lowest levels remaining almost unsplit. The reason is that the electrons in the lower levels are the inner electrons of the atoms, which are not significantly influenced by the presence of nearby atoms. On the other hand, the electrons in the higher levels are the valence electrons whose wave- functions overlap appreciably.

Fig. shows the formation of energy bands for some of the higher energy levels of isolated sodium atoms (whose ground- state configuration is 1s 2s 2p 3s) as their interatomic distance decreases. (The dashed line indicate the observed interatomic separation in solid sodium.) The 3s levels are the first 'occupied levels to be split into a band; the 2p levels do not begin to split until the interatomic distance becomes smaller than actually found in the solid sodium. (The levels 1s and 2s do not split at all.)



Semiconductors-theory & definition:

Semiconductors are the materials whose electrical conductivity lies in between metals and insulator. The energy band structure of the semiconductors is similar to the insulators but in their case, the size of the forbidden energy gap is much smaller than that of the insulator. In this class of crystals, the forbidden gap is of the order of about lev, and the two energy bands are distinctly separate with ΠΟ overlapping. At absolute "0" temperature, no electron has any energy even to jump the forbidden gap and reach the conduction band. Therefore the substance is an insulator. But when we heat the crystal and thus provide some energy to the atoms and their electrons, it becomes an easy matter for some electrons to jump the small (I ev) energy gap and go to conduction band. Thus at higher temperatures, the crystal becomes a conductors. This is the specific property of the crystal which is known as a semiconductor.



Classification of materials into conductors, insulators and semiconductors on the basis of energy band structure:

Metals are good conductors of electricity, insulators do not conduct electricity while the semiconductors hold a conductivity intermediate between that of conductors and insulators. This distinction among materials can be explained from their energy-band structures.

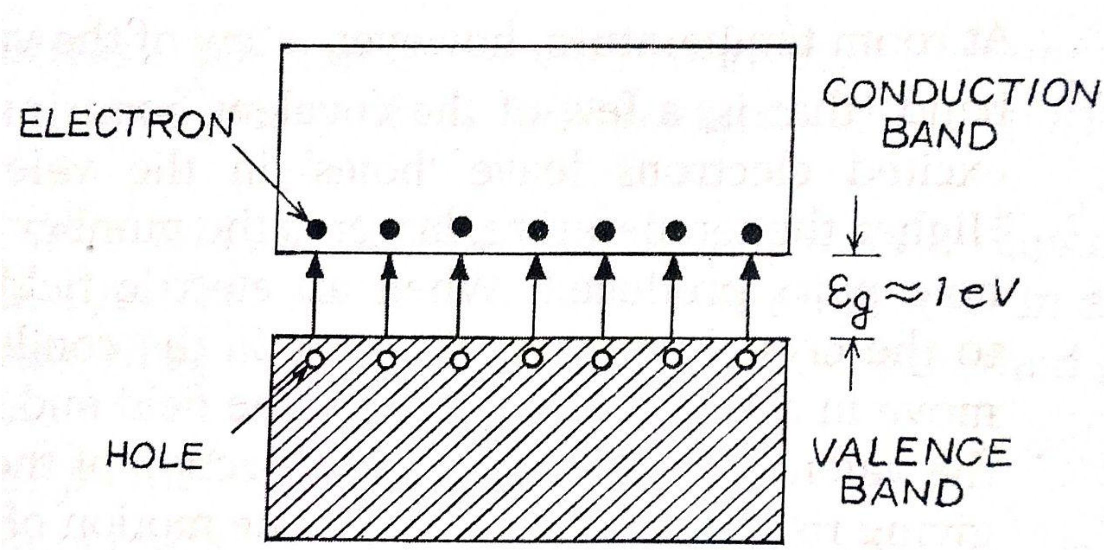
Effect of temperature on conductivity of Semiconductor:

At OK, all semiconductors are insulators. The valence band at absolute zero is completely filled and there are no free electrons in conduction band. At room temperature the electrons jump to the conduction band due to the thermal energy. When the temperature increases, a large number of electrons cross over the forbidden gap and jump from valence to conduction band. Hence conductivity of semiconductor increases with temperature.

Electrons and Holes in Semiconductors:

The semiconductors are the materials whose electrical conductivity lies between the very high conductivity of metals and the very low conductivity of insulators. They are characterised by a narrow energy gap (= 1 eV) between the valence band and the conduction band. For example, germanium and silicon have energy gaps of about 0.7 and 1.1 eV respectively. At absolute zero temperature, all states (energy levels) in the valence band are full and all states in the conduction band are empty. An applied electric field cannot give so much energy to the valence electrons that they could cross the gap, and enter the conduction hand. Hence, pure semiconductors are insulators at low temperatures.

At room temperature, however, some of the valence electrons acquire thermal energy greater than g and cross over into the conduction band. A vacancy is created in the valence band at each place where an 'electron was present before moving to the conduction band. This vacancy is called a 'hole. (Since, the absence of a negative charge is equivalent to the presence of equal positive charge, a hole is a seat of positive charge of magnitude equal to the charge of an electron.) The free electrons in the conduction band and the (positive) holes created in the valence band, can move about even under a small applied field. The solid is, therefore, slightly conducting, that is, it is a semiconductor. As the temperature rises, more and more electrons cross over to the conduction band, leaving behind equal number of holes in the valence band. Thus, the conductivity of semiconductors increases (or resistance decreases) with rise in temperature.



TYPES OF SEMICONDUCTORS

Intrinsic semiconductors:

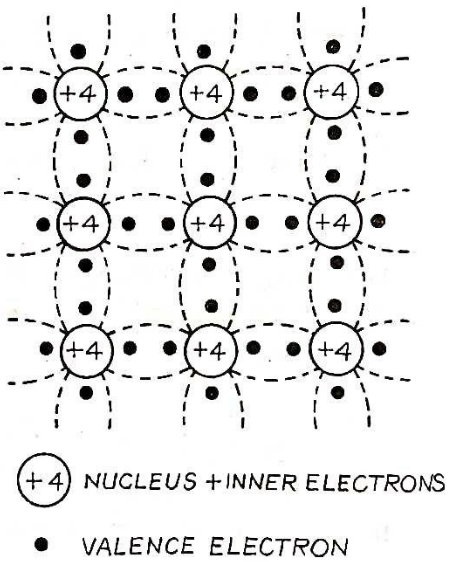
Pure semiconductors are called intrinsic semi-conductors. In a pure semiconductor, each atom behaves as if there are 8 electrons in its valence shell and therefore the entire material behaves as an insulator at low temperatures.

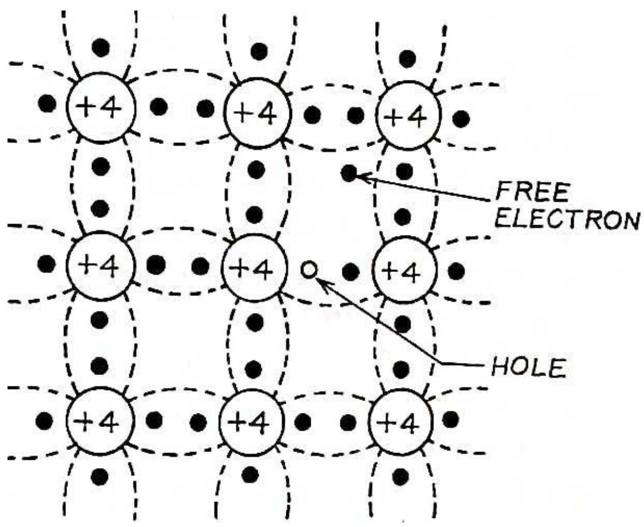
A semiconductor atom needs energy of the order of 1.1ev to shake off the valence electron. This energy becomes available to it even at room temperature. Due to thermal agitation of crystal structure, electrons from a few covalent bonds come out. The bond from which electron is freed, a vacancy is created there. The vacancy in the covalent bond is called a hole.

This hole can be filled by some other electron in a covalent bond. As an electron from covalent bond moves to fill the hole, the hole is created in the covalent bond from which the electron has moved. Since the direction of movement of the hole is opposite to that of the negative electron, a hole behaves as a positive charge carrier. Thus, at room temperature, a pure semiconductor will have electrons and holes wandering in random directions. These electrons and holes are called intrinsic carriers.

As the crystal is neutral, the number of free electrons will be equal to the number of holes. Inn intrinsic semiconductor, if n, denotes the electron number density in conduction band, n the hole number density in valence band and n, the number density or concentration of charge carriers, then

$$\mathbf{n_e = n_h = n_i}$$





Concentration of Free Electrons and Holes in an Intrinsic Semiconductor: In an intrinsic semiconductor, the concentration (number per unit volume) of electrons in conduction band, and that of holes in valence band are equal at a given temperature. Thus, if n, and n,, be the electron concentration and hole concentration respectively, we have

$$n_e = n_h = n_i,$$

where n is called the 'intrinsic concentration' or 'intrinsic charge-carrier density. For Ge, n_i = 2.4 x 1019/m^3 and for Si, n_i = 1.5 x 1016/m^3 at room temperature (300 K).

Effect of Temperature on Conductivity of Pure Semiconductors: The conductivity of a pure semiconductor increases (or the resistivity decreases) with rise in temperature. This is because, as the temperature rises, more and more of the covalent bonds in the crystal lattice break, thus creating more and more charge-carriers (electron-hole pairs). This results in increasing conductivity.

Extrinsic Semiconductors

As the conductivity of intrinsic semi-conductors is poor, so intrinsic semi-conductors are of little practical importance. The conductivity of pure semi-conductor can, however be enormously increased by addition of some pentavalent or a trivalent impurity in a very small amount (about 1 to 106 parts of the semi-conductor). The process of adding an impurity to a pure semiconductor so as to improve its conductivity is called doping. Such semi-conductors are called extrinsic semi-conductors.

Doping: The process of adding impurity to an intrinsic semiconductor in a controlled manner is called 'doping. It increases significantly the electrical conductivity of the semiconductor. The impurity atoms added are called 'dopants. Doping can be achieved in many ways. One way is to add the impurity to molten semiconductor (Ge or Si) so that it crystallises with the semiconductor. Another way is to heat the semiconductor in an atmosphere containing dopant atoms so that the latter diffuse into the semiconductor. A third method is to bombard the semiconductor with ions of dopant atoms.

Extrinsic semiconductors are of two types:
(i)n-type semiconductor
(ii)p-type semiconductor

(1) n-type Semiconductor: When a pentavalent impurity atom (antimony, phosphorus or arsenic) is added to a Ge (or Si) crystal, it replaces a Ge (or Si) atom in the crystal lattice (Fig. 9). Four of the five valence electrons of the impurity atom form covalent bonds with one valency electron each of the four Ge or Si atoms surrounding it. The fifth valence electron of the impurity atom requires little energy (only 0.01 eV in Ge lattice and 0.05 eV in Si lattice) to leave its atom. It, therefore, becomes free at room temperature (KT = 0.025 eV) to move about in the crystal and acts as a charge-carrier. Thus, by adding pentavalent impurity to pure Ge (or Si), the number of free electrons increases, that is, the conductivity of the crystal increases. The impure Ge (or Si) crystal is called an 'n-type' semiconductor because it has an excess of 'negative' charge-carriers (electrons). The impurity atoms are called 'donor atoms because they donate the conducting electrons to the crystal.

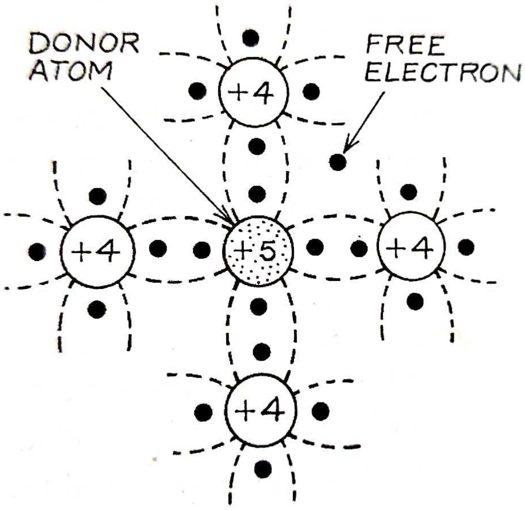
The energy-band diagram of an n-type semiconductor is shown in Fig. 10. The fifth valence electrons of the impurity atoms occupy some discrete energy levels just below the conduction band. These are called 'donor levels and are only 0.01 eV below the conduction band in case of Ge and 0.05 eV below in case of Si. Therefore, at room temperature, the "fifth" electrons of almost all the donor € atoms are thermally excited from the donor levels into the conduction band where they move as charge-carriers when an external electric field is applied. At ordinary temperature, almost all the electrons in the conduction band come from the donor levels, only a few come from the valence band. Therefore, the main charge- carriers responsible for conduction are the electrons contributed by the donors. Since, the thermal excitation from the valence band is small, there are very few holes in this band. The current contribution of the holes is therefore small. Thus, **in an n-type semiconductor the electrons are the 'majority carriers' and the holes are the 'minority carriers'.**

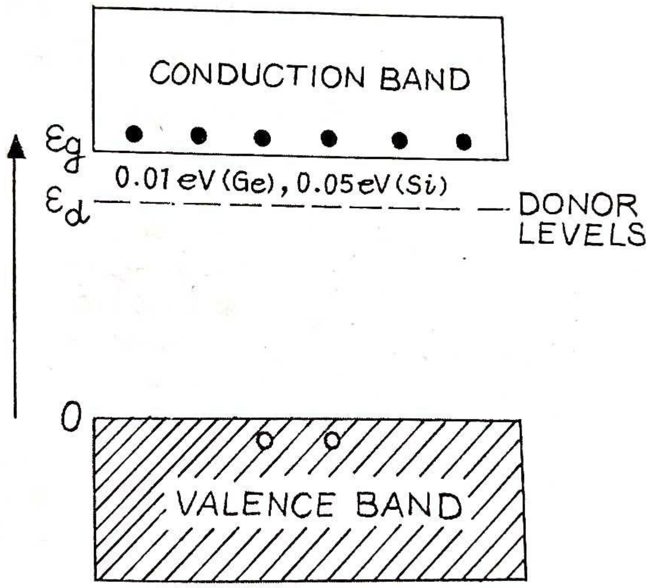
Electron and Hole Concentrations: In a doped semiconductor, the electron concentration n, and the hole concentration n are not equal (as they are in an intrinsic semiconductor). It can be shown that

$$\mathbf{n_e\, n_h = n_i^2}$$

where n is the intrinsic concentration. This is known as law of mass action'. In an n-type semiconductor, the concentration of electrons in conduction band is nearly equal to the concentration of donor atoms (N) and very large compared to the concentration of holes in valence band. That is

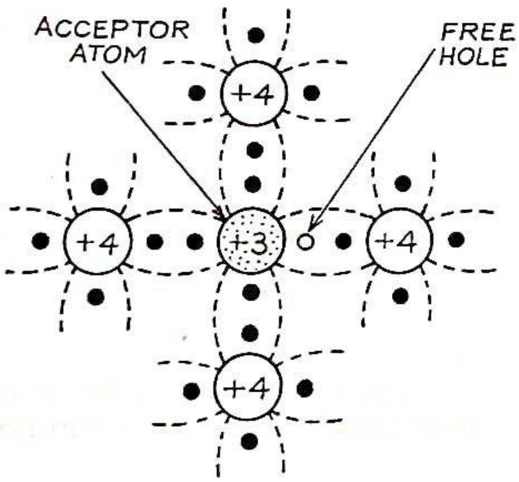
$$N_e = N_d >> n_h$$

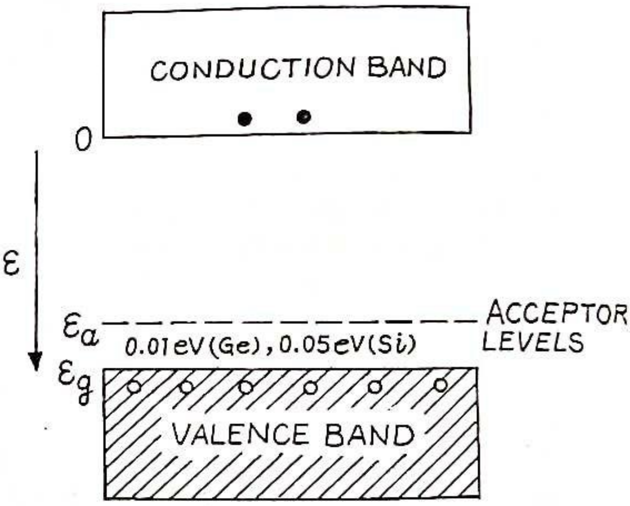




(2)p-type Semiconductor: When a trivalent impurity atom (boron, aluminium, gallium or indium) i added to a Ge (or Si) crystal, it also replaces one of the Ge (or Si) atoms in the crystal lattice (Fig. 11). Its three valence electrons form covalent bonds with one valency electron each of the three Ge (or Si) atoms surrounding it. Thus, there remains an empty space, called 'hole', on one side of the impurity atom. When an external electric field is applied, an electron bound to a neighbouring Ge (or Si) atom drops into this hole, leaving a new hole behind. This phenomenon continues and the hole moves in the crystal lattice in the direction of the applied field, acting as a positive charge-

carrier The impure Ge (or Si) crystal is called a 'p-type' semiconductor because it has an excess of positive charge-carriers (holes). The impurity atoms are called 'acceptor' atoms because they create holes which accept electrons.
The energy-band diagram of a p-type semiconductor is shown in Fig.





The impurity atoms introduce vacant discrete levels just above the top of the valence band. These are called 'acceptor levels. At room temperature, electrons are easily excited from the valence band into the acceptor levels. The corresponding holes created in the valence band are the main charge-carriers in the crystal when an electric field is applied. Thus, in a p-type semiconductor the holes are the ‘majority carriers' and the few electrons, thermally excited from the valence band into the conduction band are 'minority carriers'.

Electron and Hole Concentrations: In a p-type semiconductor, the concentration of holes in valence band is nearly equal to the concentration of acceptor atoms (N), and very large compared to the concentration of electrons in conduction band. That is,

$$\mathbf{N_h = N_a >> n_e}$$

Applications of Semiconductors

Let us now understand the uses of semiconductors in daily life. Semiconductors are used in almost all electronic devices. Without them, our life would be much different.

Their reliability, compactness, low cost and controlled conduction of electricity make them ideal to be used for various purposes in a wide range of components and devices. transistors, diodes, photosensors, microcontrollers, integrated chips and much more are made up of semiconductors.

- They are used in the designing of logic gates and digital circuits.
- These are used in microprocessors.
- They are also used in analog circuits such as oscillators and amplifiers.
- Used in high voltage applications.

Uses of Semiconductors in Everyday life

- Temperature sensors are made with

semiconductor devices.

- They are used in 3D printing machines
- Used in microchips and self-driving cars
- Used in calculators, solar plates, computers and other electronic devices.
- Transistor and MOSFET used as a switch in Electrical Circuits are manufactured using the semiconductors.
- Industrial Uses of Semiconductors
- The physical and chemical properties of semiconductors make them capable of designing technological wonders like microchips, transistors, LEDs, solar cells, etc.

The microprocessor used for controlling the operation of space vehicles, trains, robots, etc is made up of transistors and other controlling devices which are manufactured by semiconductor materials.

Importance of Semiconductors

- They are highly portable due to the smaller size
- They require less input power
- Semiconductor devices are shockproof
- They have a longer lifespan
- They are noise-free while operating

Examples of Semiconductor Devices:

These devices are said to be neither good insulators nor good conductors, hence the name 'Semi Conductors'. The semiconductor examples include the following:

- op-amps
- resistors
- capacitors
- diodes
- Transistors

These devices are widely used in many of the applications due to their reliability, compactness, low cost. As a discrete component, a semiconductor is used as optical sensors, power devices, light emitters, and also including the solid-state lasers. They also have a large range of current as well as voltage handling capacities, with the current ratings ranging from few nano-amperes i.e (10−9 ampere) up-to more than about 5,000 voltage and ampere ratings, which extend above 100,000 volts.

Semiconductor devices supply themselves in integrating into complex and are readily manufacturable into microelectronic circuits. They also find a good scope in the future in forming key components for the majority of electrical and electronic instruments and systems in various fields such as communications, data-processing, consumer, and also in industrial control equipment.

Types of Semiconductor Devices:

These devices are classified accordingly whether they are two-terminal or three-terminal devices and sometimes for terminal devices. The examples of two-terminal devices include Diode, Zener diode, Laser diode, Schottky diode, Light-emitting diode (LED), Photocell, Phototransistor, Solar cell, etc.

Some examples of three-terminal semiconductor devices include Bipolar transistor, IGBT, Field-effect transistor, Silicon-controlled rectifier, TRIAC, Thyristor, etc.

Diode:

Diodes are being for the purpose of AC voltage rectification which means restricting the voltage to follow one direction only using a capacitor or a filter, a dc voltage can be achieved. The types of diodes are:

- Zener Diode- This is used in places where voltage regulation is needed.
- P-N junction diode- It is used in photonic or optoelectronic devices and the entity is the photon. Examples are solar cells, light-emitting diodes etc

Transistors:

Transistors are of two types bipolar junction transistor and field-effect transistor. The bipolar junction transistor is achieved by the formation of two p-n junctions in two different configurations like n-p-n or p-n-p. In this type of transistor, the three regions formed are named as emitter, collector, and base or the middle region.

The field-effect transistor works on the principle of conductivity and the conductivity can be altered by the presence of an electric field.

Types of Digital Circuits:

There are special logic operational digital circuits. They are:

- NOR gate
- NAND
- NOT
- AND
- OR