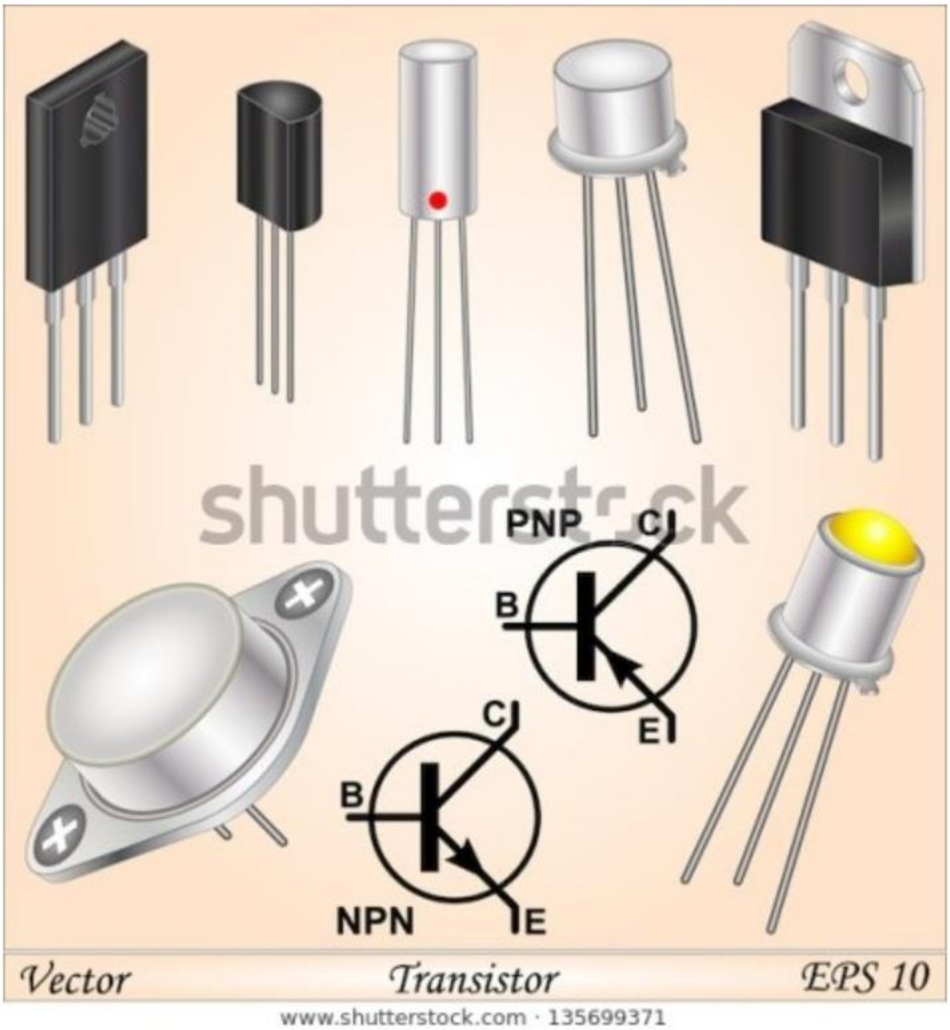
Week 2: **SOLID STATE FUNDAMENTALS**

Solid-State device



An electronic device in which electricity flows through solid semiconductor crystals (silicon, gallium, arsenide, germanium) rather than through vacuum tubes. The first solid-state device was the “cat’s whisker|” (1906), in which a fine wire was moved across a solid crystal to detect radio signal. Transistor, made of one or more semiconductors, are the heart of modern solid-state devices; in the case of integrated circuit, millions of transistors can be involved

Solid-state electronic devices are part of our everyday lives. The **transistor**, invented in 1947 by Bell Labs, was the first solid-state device to come into commercial use in the 1960s. Solid-state electronic devices have replaced **vacuum tubes** in just about all electronics devices. Vacuum tubes are still used in the transmitters of radio stations you listen to, many guitar amplifiers and some audiophile equipment. Vacuum tubes are the opposite of "solid-state" because tubes burnout, break, etc.

One of the first solid-state devices was a crystal radio. In a **crystal radio**, a piece of wire positioned on a crystal's surface is able to separate the lower-frequency audio from the higher-frequency transmitted radio carrier wave. This form of signal detection is due to the crystal's ability to pass a current in only one direction.

Solid-state refers to electronic components, devices, and systems based entirely on the semiconductor . The expression was especially prevalent in the late 1950s and early 1960s, during the transition from vacuum tube technology to the semiconductor diode and transistor . More recently, the integrated circuit (IC), the light-emitting diode (LED), and the liquid-crystal display (LCD) have evolved as further examples of solid-state devices.

In a solid-state component, the current is confined to solid elements and compounds engineered specifically to switch and amplify it. Current flows in two forms: as negatively charged electrons, and as positively charged electron deficiencies called holes. In some semiconductors, the current consists mostly of electrons; in other semiconductors, it consists mostly of holes. Both the electron and the hole are called charge carriers.

An example of a non-solid-state component is a cathode-ray tube (CRT). In this device, electrons flow freely through a vacuum from an electron gun, through deflecting and focusing fields, and finally to a phosphorescent screen.

Electronic Circuits

An electronic circuit is composed of individual electronic components, such as resistors, transistors, capacitors, inductors, diode connected by conductive wire or traces through which electric current can flow.

Insulators, Conductors & Semiconductors

Insulators

An **insulator** is a material that does not conduct electrical current under normal conditions. Most good insulators are compounds rather than single-element materials and have very high resistivity. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator. Examples of insulators are rubber, plastics, glass, mica, and quartz.

Conductors

A **conductor** is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons become free electrons. Therefore, in a conductive material the free electrons are valence electrons.

Semiconductors

A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge). Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons. Silicon is the most commonly used semiconductor.

Since their use in late 1940’s (or early 1950’s), semiconductors became the main material in the manufacturing of electronics and its variants like optoelectronics and thermoelectronics.

Before the usage of semiconductor materials in electronic devices, vacuum tubes were used design of electronic components. The main difference between vacuum tubes and semiconductor devices is that in vacuum tubes, the conduction of electrons occurs in gaseous state while in case of semiconductor device, it happens in “solid state”. Semiconductor devices can be found as both discrete components devices as well as integrated circuits.

Why Semiconductors?

The main reason for using Semiconductor Devices (and hence the underlying Semiconductor Materials) in the manufacturing of electronics devices and components is the ability to easily manipulate its conductivity of charge carriers i.e. electrons and holes.

Different Types of Semiconductor Devices

The following is a small list of some of the commonly used semiconductor devices. Based on the physical structure of the device, the following list is categorized into Two-terminal Devices and Three-terminal Devices.

Two-terminal Semiconductor Devices

- Diode
- Schottky Diode
- Light Emitting Diode (LED)
- DIAC
- Zener Diode
- Photo Diode (Photo Transistor)
- PIN Diode
- Laser Diode
- Tunnel Diode
- Photo Cell
- Solar Cell
- Gunn Diode
- IMPATT Diode
- TVS Diode (Transient Voltage Suppression Diode)
- VCSEL (Vertical Cavity Surface Emitting Laser)

Three-terminal Semiconductor Devices

- Bipolar Transistor
- Field Effect Transistor

· Insulated Gate Bipolar Transistor (IGBT)

· Darlington Transistor

· Silicon Controlled Rectifier (SCR)

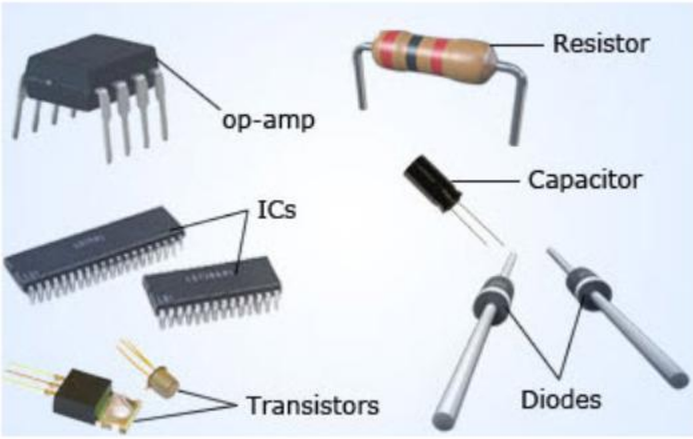
· TRIAC

· Thyristor

· Unijunction Transistor

There are also a few four-terminal semiconductors like Optocoupler (Photocoupler) and Hall-effect Sensor.

Applications of Semiconductor Devices



Semiconductor Devices

As mentioned earlier, semiconductor devices are the basis of almost all electronic devices. Some of the applications of semiconductor devices are:

· Transistors are the main components in various integrated circuits like Microprocessors.

· In fact, they are the main components in the construction of logic gates and other digital circuits.

· Transistors are also used in analog circuits like amplifiers and oscillators.

Doping

Since semiconductors are generally poor conductors, their conductivity can be drastically increased by the controlled addition of impurities to the intrinsic (pure) semiconductive material. Doping means the introduction of impurities into a semiconductor crystal to the defined modification of conductivity.

Advantages of Semiconductor Devices

· As semiconductor devices have no filaments, hence no power is needed to heat them to cause the emission of electrons.

· Since no heating is required, semiconductor devices are set into operation as soon as the circuit is switched on.

· During operation, semiconductor devices do not produce any humming noise.

· Semiconductor devices require low voltage operation as compared to vacuum tubes.

· Owing to their small sizes, the circuits involving semiconductor devices are very compact.

· Semiconductor devices are shock proof.

· Semiconductor devices are cheaper as compared to vacuum tubes.

· Semiconductor devices have an almost unlimited life.

· As no vacuum has to be created in semiconductor devices, they have no vacuum deterioration trouble.

Disadvantages of Semiconductor Devices

· The noise level is higher in semiconductor devices as compared to that in the vacuum tubes.

· Ordinary semiconductor devices cannot handle as more power as ordinary vacuum tubes can do.

· In high frequency range, they have poor responder.

Holes and Electrons in Semiconductors

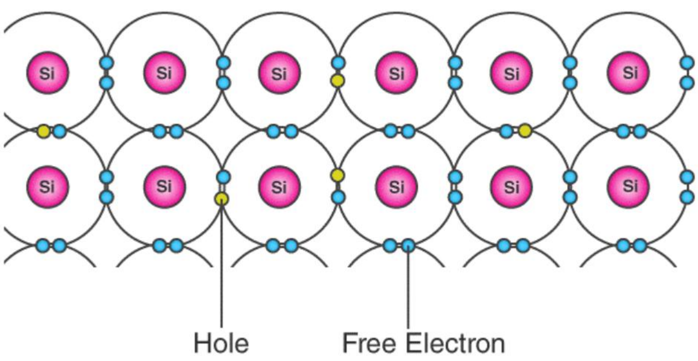
Holes and electrons are the types of charge carriers accountable for the flow of current in semiconductors. **Holes** (valence electrons) are the positively charged electric charge carrier whereas **electrons** are the negatively charged particles. Both electrons and holes are equal in magnitude but opposite in polarity.

Mobility of Electrons and Holes

In a semiconductor, the **mobility of electrons is higher than that of the holes**. It is mainly because of their different band structures and scattering mechanisms.

Electrons travel in the conduction band whereas holes travel in the valence band. When an electric field is applied, holes cannot move as freely as electrons due to their restricted movement. The elevation of electrons from their inner shells to higher shells results in the creation of holes in semiconductors. Since the holes experience stronger atomic force by the nucleus than electrons, holes have lower mobility.

The **bond model** of electrons in silicon of valency 4 is shown below. Here, when one of the free electrons (blue dots) leaves the lattice position, it creates a hole (grey dots). This hole thus created takes the opposite charge of the electron and can be imagined as positive charge carriers moving in the lattice.

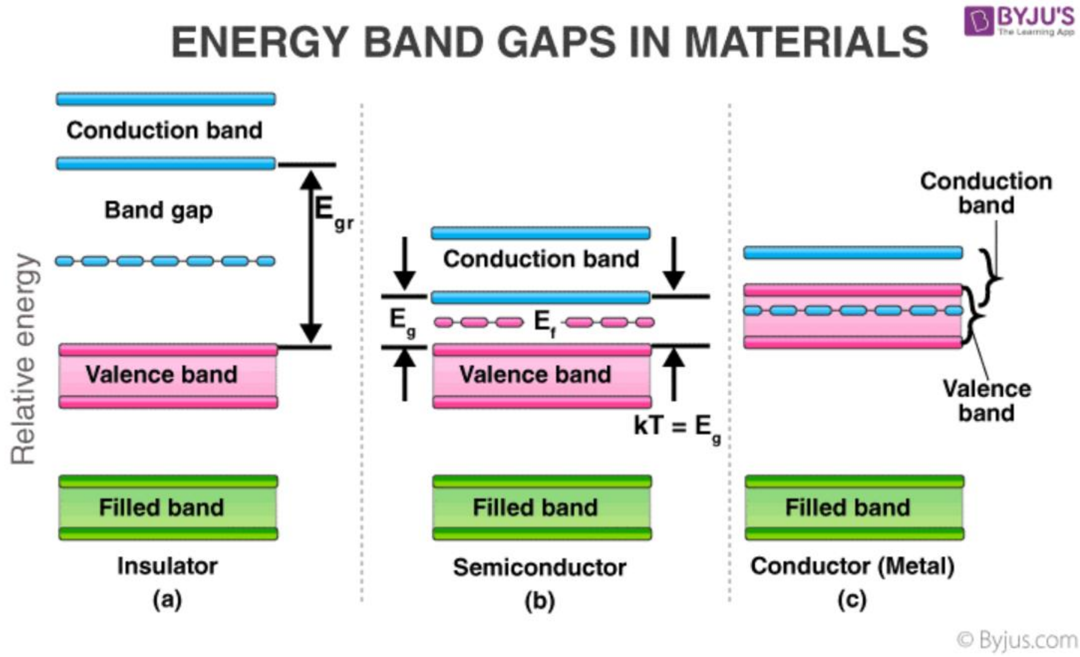


Concept of Electrons and Holes in Semiconductors

Band Theory of Semiconductors

The introduction of band theory happened during the quantum revolution in science. Walter Heitler and Fritz London discovered the energy bands.

We know that the electrons in an atom are present in different energy level. When we try to assemble a lattice of a solid with N atoms, then each level of an atom must split up into N levels in the solid. This splitting up of sharp and tightly packed energy levels forms **Energy Bands**. The gap between adjacent bands representing a range of energies that possess no electron is called a **Band Gap**.



Energy Band Diagram for Semiconductors, Conductors, and Insulators

Conduction Band and Valence Band in Semiconductors

Valence Band:

The energy band involving the energy levels of valence electrons is known as the valence band. It is the highest occupied energy band. When compared with insulators, the bandgap in semiconductors is smaller. It allows the electrons in the valence band to jump into the conduction band on receiving any external energy.

Conduction Band:

It is the lowest unoccupied band that includes the energy levels of positive (holes) or negative (free electrons) charge carriers. It has conducting electrons resulting in the flow of current. The conduction band possess high energy level and are generally empty. The conduction band in semiconductors accepts the electrons from the valence band.

What is Fermi Level in Semiconductors?

Fermi level (denoted by EF) is present between the valence and conduction bands. It is the highest occupied molecular orbital at absolute zero. The charge carriers in this state have their own quantum states and generally do not interact with each other.

When the temperature rises above absolute zero, these charge carriers will begin to occupy states above Fermi level.

In a **p-type semiconductor**, there is an increase in the density of unfilled states. Thus, accommodating more electrons at the lower energy levels. However, in an **n-type semiconductor**, the density of states increases, therefore, accommodating more electrons at higher energy levels.

Properties of Semiconductors

Semiconductors can conduct electricity under preferable conditions or circumstances. This unique property makes it an excellent material to conduct electricity in a controlled manner as required.

Unlike conductors, the charge carriers in semiconductors arise only because of external energy (thermal agitation). It causes a certain number of valence electrons to cross the energy gap and jump into the conduction band, leaving an equal amount of unoccupied energy states, i.e. holes. Conduction due to electrons and holes are equally important.

- **Resistivity:** 10^{-5} to 10^{6} Ωm
- **Conductivity:** 10^{5} to 10^{-6} mho/m
- **Temperature coefficient of resistance:** Negative
- **Current Flow:** Due to electrons and holes

Why does the Resistivity of Semiconductors go down with Temperature?

The difference in resistivity between conductors and semiconductors is due to their difference in charge carrier density.

The resistivity of semiconductors decreases with temperature because the number of charge carriers increases rapidly with increase in temperature, making the fractional change i.e. the temperature coefficient negative.

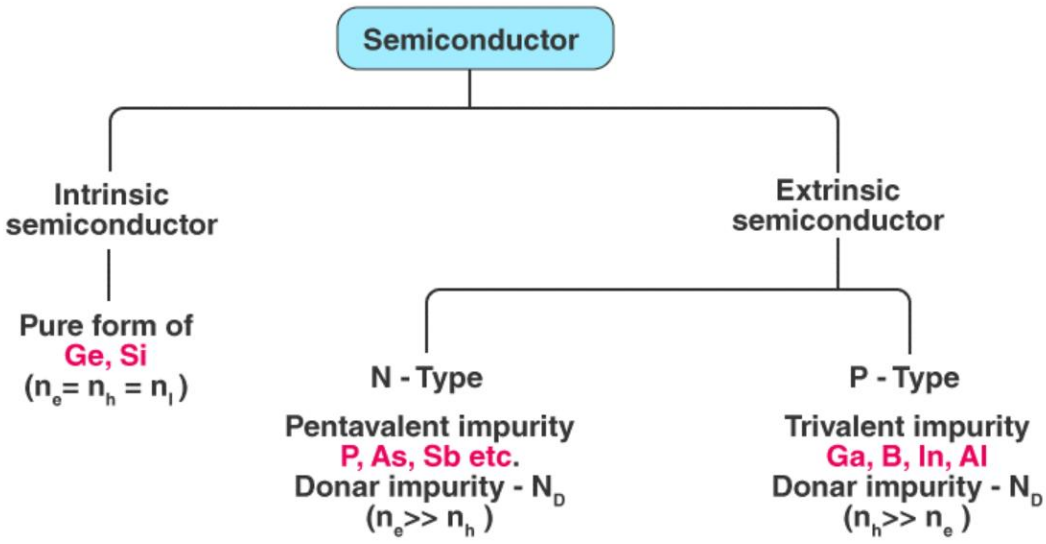
Some Important Properties of Semiconductors are:

1. Semiconductor acts like an insulator at Zero Kelvin. On increasing the temperature, it works as a conductor.
2. Due to their exceptional electrical properties, semiconductors can be modified by doping to make semiconductor devices suitable for energy conversion, switches, and amplifiers.
3. Lesser power losses.
4. Semiconductors are smaller in size and possess less weight.
5. Their resistivity is higher than conductors but lesser than insulators.
6. The resistance of semiconductor materials decreases with the increase in temperature and vice-versa.

Types of Semiconductors

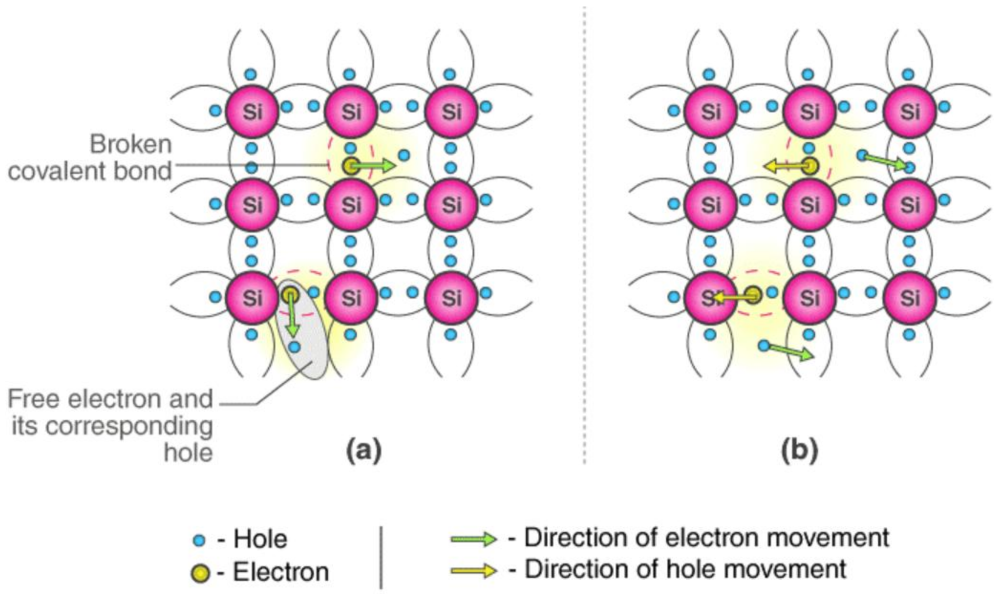
Semiconductors can be classified as:

- Intrinsic Semiconductor
- Extrinsic Semiconductor



Intrinsic Semiconductor

An **intrinsic type of semiconductor material** is made to be very pure chemically. It is made up of only a single type of element.



Conduction Mechanism in Case of Intrinsic Semiconductors (a) In absence of electric field (b) In presence of electric Field

Germanium (Ge) and Silicon (Si) are the most common type of intrinsic semiconductor elements. They have four valence electrons (tetravalent). They are bound to the atom by covalent bond at absolute zero temperature.

When the temperature rises, due to collisions, few electrons are unbounded and become free to move through the lattice, thus creating an absence in its original position (hole). These free electrons and holes contribute to the conduction of electricity in the semiconductor. The negative and positive charge carriers are equal in number.

The thermal energy is capable of ionizing a few atoms in the lattice, and hence their conductivity is less.

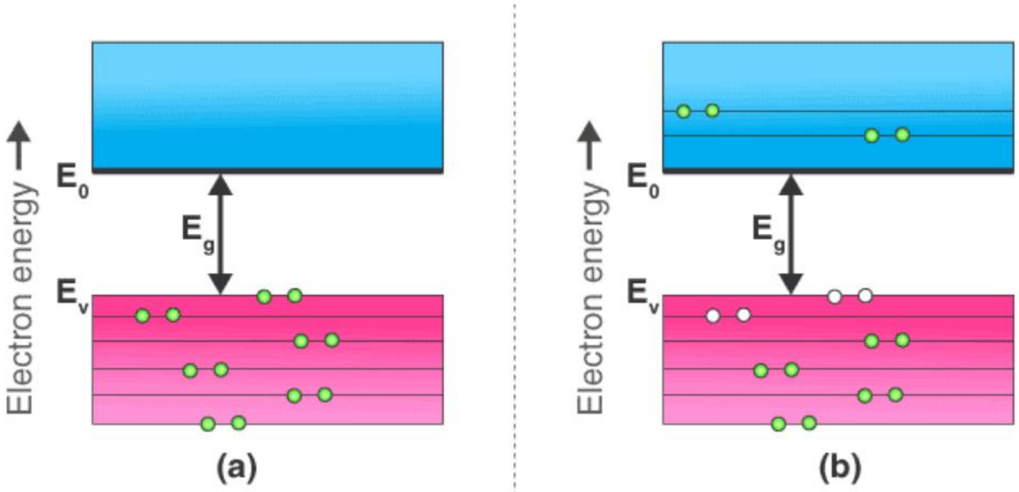
The Lattice of Pure Silicon Semiconductor at Different Temperatures

· **At absolute zero Kelvin temperature:** At this temperature, the covalent bonds are very strong and there are no free electrons and the semiconductor behaves as a perfect insulator.

· **Above absolute temperature:** With the increase in temperature few valence electrons jump into the conduction band and hence it behaves like a poor conductor.

Energy Band Diagram of Intrinsic Semiconductor

The energy band diagram of an intrinsic semiconductor is shown below:



(a) Intrinsic Semiconductor at T = 0 Kelvin, behaves like an insulator (b) At t>0, four thermally generated electron pairs

In intrinsic semiconductors, current flows due to the motion of free electrons as well as holes. The total current is the sum of the electron current I_e due to thermally generated electrons and the hole current I_h

Total Current (I) = $I_e + I_h$

For an intrinsic semiconductor, at finite temperature, the probability of electrons to exist in conduction band decreases exponentially with increasing bandgap (E_g)

$n = n_0 e^{-Eg/2.Kb.T}$

Where,

· Eg = Energy bandgap

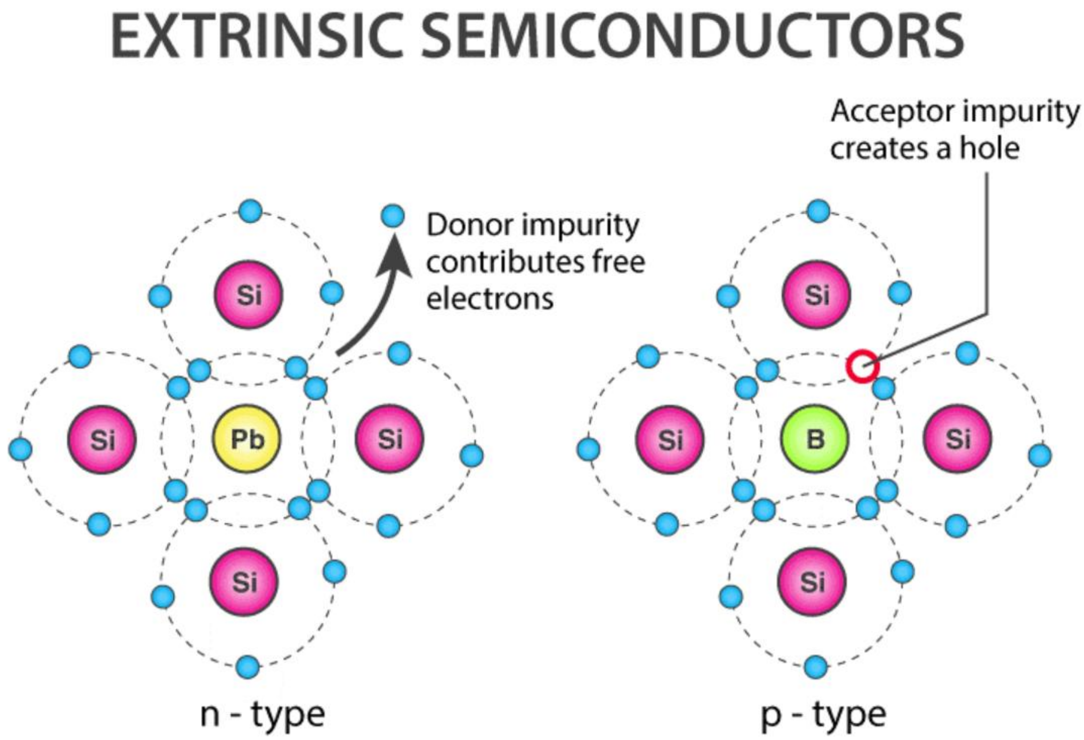
· K_b = Boltzmann's constants

Extrinsic Semiconductor

The conductivity of semiconductors can be greatly improved by introducing a small number of suitable replacement atoms called IMPURITIES. The process of adding impurity atoms to the pure semiconductor is called DOPING. Usually, only 1 atom in 10^7 is replaced by a dopant atom in the doped semiconductor. An extrinsic semiconductor can be further classified into:

· N-type Semiconductor

· P-type Semiconductor



Classification of Extrinsic Semiconductor

N-Type Semiconductor

- Mainly due to electrons
- Entirely neutral
- Majority – Electrons and Minority – Holes

When a pure semiconductor (Silicon or Germanium) is doped by pentavalent impurity (P, As, Sb, Bi) then, four electrons out of five valence electrons bonds with the four electrons of Ge or Si.

The fifth electron of the dopant is set free. Thus the impurity atom donates a free electron for conduction in the lattice and is called "**Donar**".

Since the number of free electron increases by the addition of an impurity, the negative charge carriers increase. Hence it is called n-type semiconductor.

Crystal as a whole is neutral, but the donor atom becomes an immobile positive ion. As conduction is due to a large number of free electrons, the electrons in the n-type semiconductor are the MAJORITY CARRIERS and holes are the MINORITY CARRIERS.

P-Type Semiconductor

- Mainly due to holes
- Entirely neutral
- Majority – Holes and Minority – Electrons

When a pure semiconductor is doped with a trivalent impurity (B, Al, In, Ga) then, the three valence electrons of the impurity bonds with three of the four valence electrons of the semiconductor.

This leaves an absence of electron (hole) in the impurity. These impurity atoms which are ready to accept bonded electrons are called "**Acceptors**".

With the increase in the number of impurities, holes (the positive charge carriers) are increased. Hence, it is called p-type semiconductor.

Crystal as a whole is neutral, but the acceptors become an immobile negative ion. As conduction is due to a large number of holes, the holes in the p-type semiconductor are MAJORITY CARRIERS and electrons are MINORITY CARRIERS.

Difference Between Intrinsic and Extrinsic Semiconductors

Intrinsic Semiconductor	**Extrinsic Semiconductor**
Pure semiconductor	Impure semiconductor
Density of electrons is equal to the density of holes	Density of electrons is not equal to the density of holes
Electrical conductivity is low	Electrical conductivity is high
Dependence on temperature only	Dependence on temperature as well as on the amount of impurity
No impurities	Trivalent impurity, pentavalent impurity

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.

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

Here we have discussed some advantages of semiconductors which makes them highly useful everywhere.

- 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