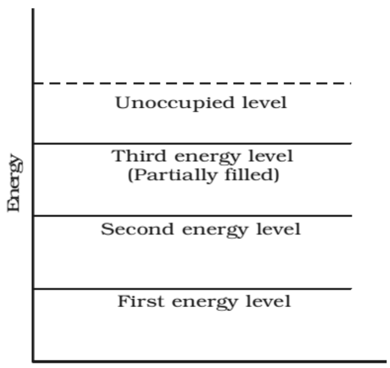
Semiconductors

A material which has resistivity between conductors and insulators is known as semiconductor. The resistivity of a semiconductor lie approximately between $10^{-2}\,\Omega$m and $10^{4}\,\Omega$ m at room temperature. The resistance, R of a semiconductor decreases with increase in temperature over a particular temperature range. This behaviour is contrary to that of a metallic conductor for which the resistance, R increases with increase in temperature. The elements that are classified as semiconductors are non-metals; Si, Ge, etc. Germanium and silicon are most widely used as semiconductors.

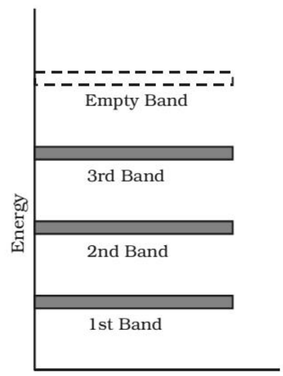
Energy band in solids

In the case of a single isolated atom, there are various discrete energy levels. (Normally called orbits)

When many atoms are brought very close during bonding, the permissible energy levels increases. 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.

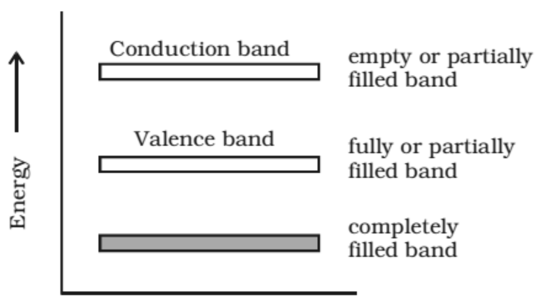


Energy levels of a single isolated silicon atom



Energy bands in a silicon solid

The completely filled levels are known as **core levels** and the electrons filling these levels are called core electrons. The electrons in the outermost level are called **valence electrons**. The partially filled outermost level is valence level and the permitted levels which are vacant are known as conduction levels.



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 transferred from valence band to conduction band, external energy is required, which is equal to the forbidden energy gap.

Insulators, semiconductors and conductors

Insulators

Their forbidden energy gap is very large; it 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. A good example: 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.

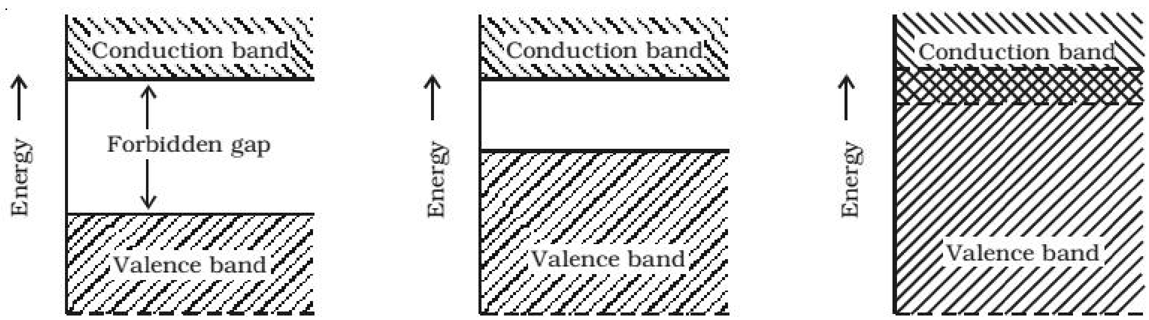
When the temperature is increased, some electrons will move to the conduction band. This is the reason, why certain materials, which are insulators at room temperature become conductors at high temperature. The resistivity of insulator approximately lies between 10^{11} and 10^{16} Ω m.

Semiconductors

Their forbidden gap is very small; it is of the order of 0.7eV for Ge and 1.1eV for Si.. Germanium and silicon are the best examples of semiconductors. There are no electrons in the conduction band. The valence band is completely filled at 0 K. 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 Ω m.

Conductors

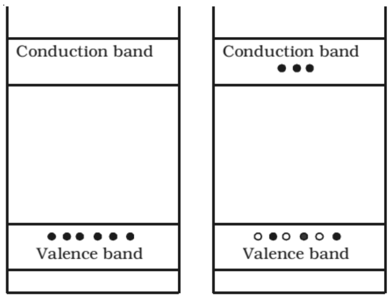
There is no forbidden gap available, the valence and conduction band overlap each other. The electrons from valence band freely enter into the conduction band. Due to the overlapping of the valence and conduction bands, a very low potential difference can cause the continuous flow of current.



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

Electrons and holes in semiconductors

These are charge carriers in semiconductors. For an intrinsic semiconductor (Pure semiconductor) at absolute zero temperature the electrons move in to the conduction band at high temperatures. In the valence band, a vacancy is created at the place where the electron was present, before it had moved in to the conduction band. This vacancy is called hole.



An electron from the neighbouring atom can break the covalent bond and can occupy this hole, creating a hole at another place. Since an electron has a unit negative charge, the hole is associated with a unit positive charge. The importance of hole is that, it may serve as a carrier of electricity in the same manner as the free electron, but in the opposite direction.

Intrinsic semiconductor

This is a semiconductor which is pure and contains no impurity. In an intrinsic semiconductor, the number of free electrons and holes are equal. Common examples of intrinsic semiconductors are pure germanium and silicon.

The forbidden energy gap is so small that even at ordinary room temperature, there are many electrons which possess sufficient energy to cross the forbidden energy gap and enter into the conduction band.

Doping a semiconductor

This is a process of adding small amount of impurity into an intrinsic semiconductor to generate free electrons or holes as charge carriers.

The semiconductor containing impurity atoms is known as impure or doped or extrinsic semiconductor.

The impurity atoms are called dopants. The doping material is either pentavalent atoms (bismuth, antimony, phosphorous, arsenic which have five valence electrons) or trivalent atoms (aluminium, gallium, indium, boron which have three valence electrons). The pentavalent doping atom is known as donor atom, since it donates one electron to the conduction band of pure semiconductor. The trivalent atom is called an acceptor atom, because it accepts one electron from the pure semiconductor atom.

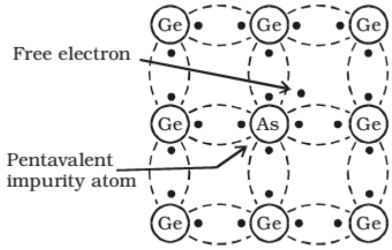
Extrinsic semiconductor

An extrinsic semiconductor is one in which an impurity with a valency higher or lower than the valency of the pure semiconductor is added, so as to increase the electrical conductivity of the semiconductor.

Depending upon the type of impurity atoms added, an extrinsic semiconductor can be classified as N-type or P-type.

N-type semiconductor

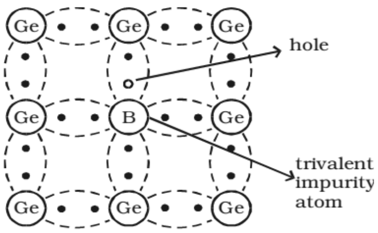
When a small amount of pentavalent impurity such as arsenic is added to a pure germanium semiconductor crystal, the resulting crystal is called N-type semiconductor.



The four valence electrons of arsenic atom form covalent bonds with electrons of neighbouring four germanium atoms. The fifth electron of arsenic atom is loosely bound. This electron can move about almost as freely as an electron in a conductor and hence it will be the carrier of current. The number of electrons increases, compared to the available number of charge carriers in the intrinsic semiconductor. Free electrons are the majority charge carriers and holes are the minority charge carriers.

P-type semiconductor

When a small amount of trivalent impurity (such as indium, boron or gallium) is added to a pure semiconductor crystal, the resulting semiconductor crystal is called P-type semiconductor.

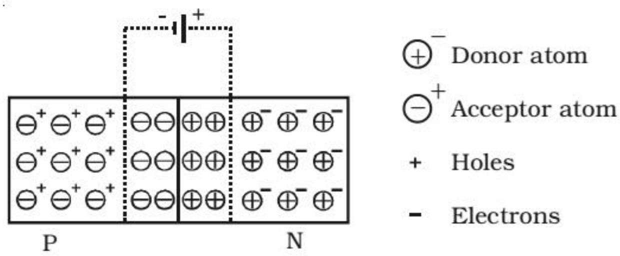


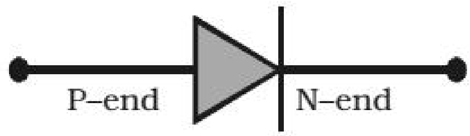
The three valence electrons of the boron atom form covalent bonds with valence electrons of three neighbourhood germanium atoms. In the fourth covalent bond, only one valence electron is available from germanium atom and there is deficiency of one electron which is called as a hole. Hence for each boron atom added, one hole is created. Since the holes can accept electrons from neighbourhood, the impurity is called acceptor.

Since the hole is associated with a positive charge moving from one position to another, this is called as P-type semiconductor. In P-type semiconductors, holes are the majority charge carriers and free electrons are the minority charge carriers.

PN Junction diode

This is a junction where one side of a single crystal of pure semiconductor (Ge or Si) is doped with acceptor impurity atoms and the other side is doped with donor impurity atoms. P region has a high concentration of holes and N region contains a large number of electrons.



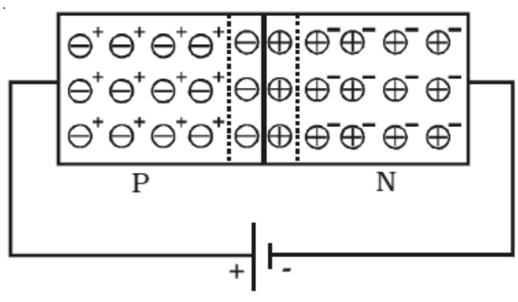


As soon as the junction is formed, free electrons and holes cross through the junction by the process of diffusion. During this process, the electrons crossing the junction from N-region into the P region, recombine with holes in the P-region very close to the junction. Similarly holes crossing the junction from the P-region into the N-region, recombine with electrons in the N-region very close to the junction. Thus a region is formed, which does not have any mobile charges very close to the junction. This region is called **depletion region**. In this region, on the left side of the junction, the acceptor atoms become negative ions and on the right side of the junction, the donor atoms become positive ions.

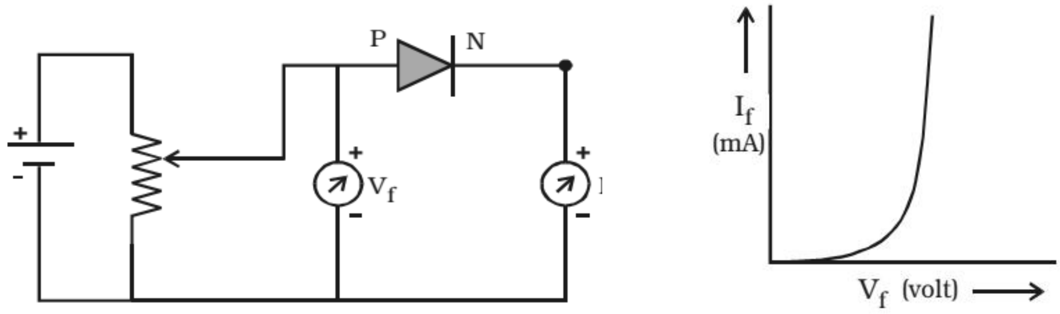
An electric field is set up, between the donor and acceptor ions in the depletion region. The potential at the N-side is higher than the potential at P-side. Therefore electrons in the N-side are prevented to go to the lower potential of P-side. Similarly, holes in the P-side find themselves at a lower potential and are prevented to cross to the N-side. Thus, there is a barrier at the junction which opposes the movement of the majority charge carriers. The difference of potential from one side of the barrier to the other side is called potential barrier. The potential barrier is approximately 0.7V for a silicon PN junction and 0.3V for a germanium PN junction. The distance from one side of the barrier to the other side is called the width of the barrier, which depends upon the nature of the material.

Forward biased PN junction diode

When the positive terminal of the battery is connected to P-side and negative terminal to the N-side, so that the potential difference acts in opposite direction to the barrier potential, then the P-N junction diode is said to be forward biased.

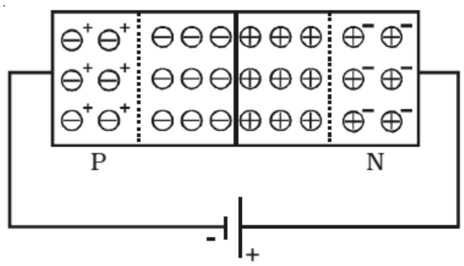


The applied positive potential repels the holes in the P-region, and the applied negative potential repels the electrons in the N-region, so the charges move towards the junction. If the applied potential difference is more than the potential barrier, some holes and free electrons enter the depletion region. Hence, the potential barrier as well as the width of the depletion region are reduced. The positive donor ions and negative acceptor ions within the depletion region regain electrons and holes respectively. As a result of this, the depletion region disappears and the potential barrier also disappears. Hence, under the action of the forward potential difference, the majority charge carriers flow across the junction in opposite direction and constitute current flow in the forward direction. The diagram shows a forward circuit and I-V characteristic.

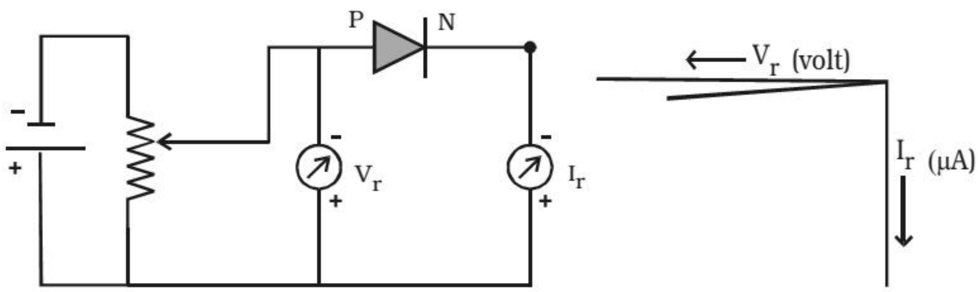


Reverse biased PN junction diode

When the positive terminal of the battery is connected to the N-side and negative terminal to the P-side, so that the applied potential difference is in the same direction as that of barrier potential, the junction is said to be reverse biased.



When the PN junction is reverse biased electrons in the N region and holes in the P-region are attracted away from the junction. Because of this, the number of negative ions in the P-region and positive ions in the N-region increases. Hence the depletion region becomes wider and the potential barrier is increased. Since the depletion region does not contain majority charge carriers, it acts like an insulator. Therefore, no current should flow in the external circuit. But, in practice, a very small current of the order of few microamperes flows in the reverse direction. This is due to the minority carriers flowing in the opposite direction. This reverse current is small, because the number of minority carriers in both regions is very small. Since the major source of minority carriers is, thermally broken covalent bonds, the reverse current mainly depends on the junction temperature.



(a) Diode circuit–Reverse bias *(b) Reverse characteristics*