Theory of Semiconductor Devices

Semiconductor:

A semiconductor is a substance which has resistivity (10-4 to 0.5 Ωm) in between conductors and insulators e.g. germanium, silicon, selenium, carbon etc.

Properties:

I. The resistivity of a semiconductor is less than an insulator but more than a conductor.

II. Semiconductors have negative temperature co-efficient of resistance i.e. the resistance of a semiconductor decreases with the increase in temperature and vice-versa. For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.

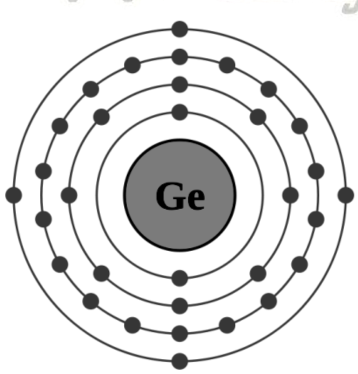
III. When a suitable metallic impurity (e.g. arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably.

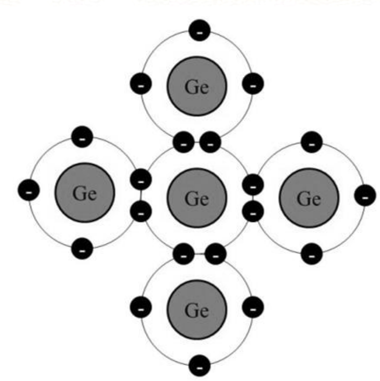
Commonly used Semi conductors:

The two most frequently used materials are germanium (Ge) and silicon (Si). It is because the energy required to break their co-valent bonds is very small; being about 0.7 eV for germanium and about 1.1 eV for silicon.

Germanium:

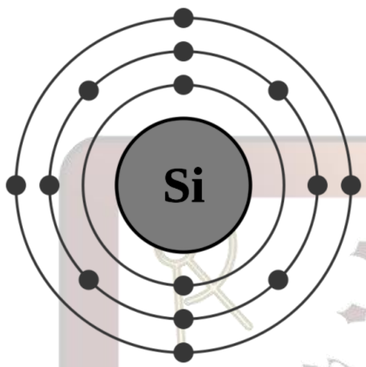
Germanium has become the model substance among the semiconductors; the main reason being that it can be purified relatively well and crystallized easily. Germanium is an earth element at first it is recovered from the ash of certain coals or from the flue dust of zinc smelters. Generally, recovered germanium is in the form of germanium dioxide powder which is then reduced to pure germanium. The atomic number of germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outer or valence orbit. Germanium atom has four valence electrons *i.e.*, it is a tetravalent element.

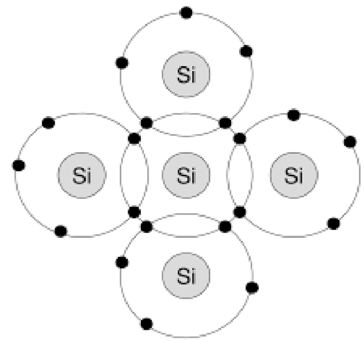




Silicon:

Silicon is a most common element in most of the rocks. Sand is silicon dioxide. The silicon compounds are chemically reduced to silicon which is 100% pure for use as a semiconductor. The atomic number of silicon is 14. Therefore, it has 14 protons and 14 electrons. Two electrons are in the first orbit, eight electrons in the second orbit and four electrons in the third orbit. Silicon atom has four valence electrons i.e. it is a tetravalent element.



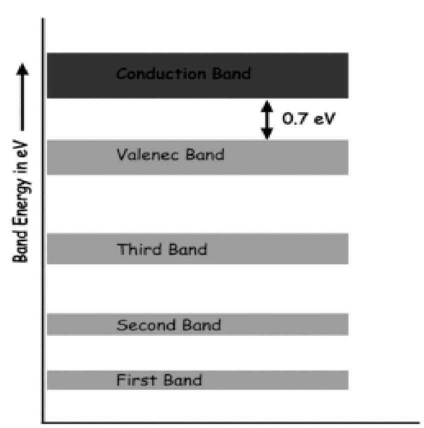


Energy Band description of semiconductor:

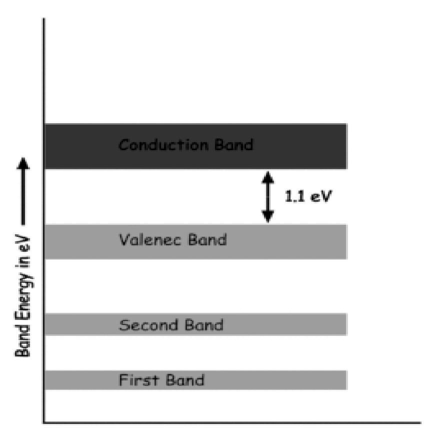
A semiconductor is a substance whose resistivity lies between conductors and insulators. The resistivity is of the order of 10^{-4} to 0.5 ohm metre. However, a semiconductor can be defined much more comprehensively on the basis of energy bands,

A semiconductor is a substance which has almost filled valence band and nearly empty conduction band with a very small energy gap (1 eV) separating the two.

The forbidden energy gap between valence band and conduction band is very small; being 1.1 eV for silicon and 0.7 eV for germanium. Therefore, relatively small energy is needed by their valence electrons to cross over to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter into the conduction band and thus become free electrons. However, at this temperature, the number of free electrons available is very small. Therefore, at room temperature, a piece of silicon or germanium is neither a good conductor nor an insulator. For this reason, such substances are called semiconductors.



Germanium



Silicon

The electrical conductivity of a semiconductor changes appreciably with temperature variations.

At absolute zero:

At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons are engaged in co-valent bonding. At this temperature, the co-valent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator.

In terms of energy band description, the valence band is filled and there is a large energy gap between valence band and conduction band. Therefore, no valence electron can reach the conduction band to become free electron. It is due to the non-availability of free electrons that a semiconductor behaves as an insulator.

Above absolute zero:

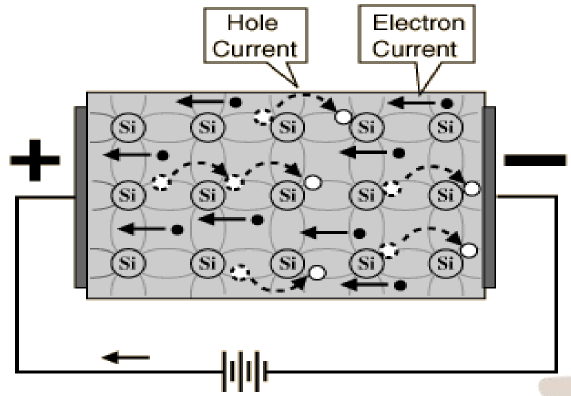
When the temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons free which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semiconductor crystal. Thus the resistance of a semiconductor decreases with the rise in temperature i.e. it has negative temperature coefficient of resistance. It may be added that at room temperature, current through a semiconductor is too small to be of any practical value.

In terms of energy band, as the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current.

Hole Current:

At room temperature, some of the co-valent bonds in pure semiconductor break, setting up free electrons. Each time a valence electron enters into the conduction band, a hole is created in the valence band. Under the influence of electric field, the free electrons constitute electric current. At the same time, another current due to the hole also flows in the semiconductor. When a covalent bond is broken due to thermal energy, the removal of one electron leaves a vacancy in the covalent bond. This vacant place is called a hole which acts as a positive charge. For one electron set free, one hole is created. Therefore, thermal energy creates hole-electron pairs; there being as many holes as the free electrons.

Suppose the valence electron at a position say '***A***' in the co-valent bond has become free electron due to thermal energy. This creates a hole in that position '***A***'. The hole is a strong centre of attraction for the electron. A valence electron from nearby co-valent bond say at position '***B***' comes to fill that hole. This results in the creation of hole at the position '***B***'. Another valence electron say at position '***C***' in turn may leave its bond to fill the newly created hole at position '***B***', thus creating a hole at new position '***C***'. Thus the hole having a positive charge has moved from positive terminal to the negative terminal (A, B, C) of supply. This current is called hole current.

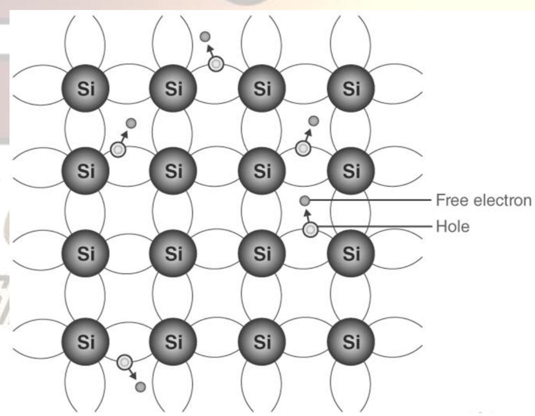


Type Of semiconductors:

Intrinsic Semiconductors:

A semiconductor in an extremely pure form is known as an intrinsic semiconductor.

In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes, by free electrons and holes. The free electrons are produced due to the breaking up of some covalent bonds by thermal energy. At the same time, holes are created in the covalent bonds. Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.



Extrinsic Semiconductors:

A semiconductor with added impurities to increase the conducting properties is known as an extrinsic semiconductor.

The intrinsic semiconductor has little current conduction capability at room temperature. The pure semiconductor must be altered so as to significantly increase its conducting properties to be useful in electronic devices. This is achieved by adding a small amount of suitable impurity to an intrinsic semiconductor. It is extrinsic semiconductor. The process of adding impurities to a semiconductor is known as doping. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, for 108 atoms of semiconductor, one impurity atom is added. The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal. If a pentavalent impurity (having 5 valence electrons) is added to the semiconductor, a large number of free electrons are produced in the semiconductor.

On the other hand, addition of trivalent impurity (having 3 valence electrons) creates a large number of holes in the semiconductor crystal.

Depending upon the type of impurity added, extrinsic semiconductors are classified into two types:

- **P-type** semiconductor
- **N-type** semiconductor

P-type semiconductors:

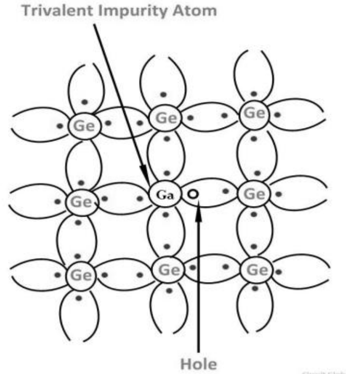
When a small amount of trivalent impurity is added to a pure semiconductor, it is called p-type semiconductor.

The trivalent impurity provides a large number of holes in the semiconductor. The examples of trivalent impurities are gallium (Atomic. No. 31) and indium (Atomic. No. 49). Such impurities which produce p-type semiconductor are known as acceptor impurities because the holes created can accept the electrons.

For a p-type semiconductor consider a pure germanium crystal. When a small amount of trivalent impurity, gallium is added to germanium crystal, a large number of holes are created in the crystal, because gallium atom's has three valence electrons. For each atom of gallium only three co-valent bonds can be formed. It is because three valence electrons of gallium atom can form only three single co-valent bonds with three germanium atoms. In the fourth co-valent bond, only germanium atom contributes one valence electron while gallium has no valence electron to contribute as all its three valence electrons are already engaged in the co-valent bonds with neighboring germanium atoms. In other words, fourth bond is incomplete; there is a short of one electron. This missing electron is called a hole. Therefore, for each gallium atom added, one hole is created. A small amount of gallium provides millions of holes.

P-type conductivity:

The current conduction in p-type semiconductor is predominantly by holes i.e. positive charges and is called p-type conductivity. When potential difference is applied to the p-type semiconductor, the holes (by the impurity) are shifted from one co-valent bond to another. As the holes are positively charged, therefore, they are directed towards the negative terminal, constituting hole current. It may be noted that in p-type conductivity, the valence electrons move from one co-valent bond to another unlike the n-type where current conduction is by free electrons.



N-type semiconductors:

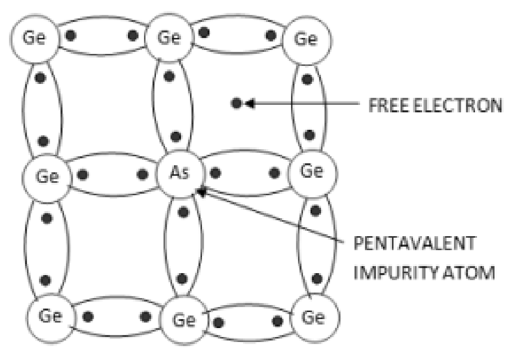
When a small amount of pentavalent impurity is added to a pure semiconductor, it is called as **n-type semiconductor.**

The pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Examples of pentavalent impurities are arsenic (Atomic. No. 33) and antimony (Atomic. No. 51). Such impurities which produce n-type semiconductor are known as donor impurities because they donate or provide free electrons to the semiconductor crystal.

To explain the formation of n-type semiconductor, consider a pure germanium crystal. We know that germanium atom has four valence electrons. When a small amount of pentavalent impurity like arsenic is added to germanium crystal, a large number of free electrons become available in the crystal. The reason is simple. Arsenic is pentavalent i.e. its atom has five valence electrons. An arsenic atom fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms. The fifth valence electron of arsenic atom finds no place in co-valent bonds and is thus free. Therefore, for each arsenic atom added, one free electron will be available in the germanium crystal. Though each arsenic atom provides one free electron, yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

N-type conductivity:

The current conduction in an n-type semiconductor is predominantly by free electrons i.e. negative charges and is called n-type conductivity. When potential differences is applied across the n-type semiconductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current. As the current flow through the crystal is by free electrons which are carriers of negative charge, therefore, this type of conductivity is called negative or n-type conductivity.



Majority and minority carrier:

Due to the effect of impurity, n-type material has a large number of free electrons whereas p-type material has a large number of holes. However, it may be recalled that even at room temperature, some of the co-valent bonds break, thus releasing an equal number of free electrons and holes. An n-type material has its share of electron-hole pairs (released due to breaking of bonds at room temperature) but in addition has a much larger quantity of free electrons due to the effect of impurity. These impurity-caused free electrons are not associated with holes. Consequently, an n-type material has a large number of free electrons and a small number of holes. The free electrons in this case are considered majority carriers — since the major portion of current in n-type material is by the flow of free electrons — and the holes are the minority carriers. Similarly, in a p-type material, holes outnumber the free electrons. Therefore, holes are the majority carriers and free electrons are the minority carriers.