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## Unit- 14. Semiconductor Electronics

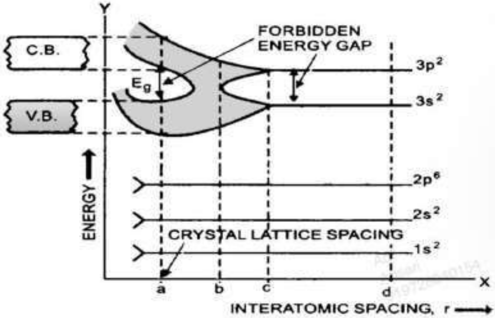
# 14. Semiconductor Electronics

## Semiconductors

The materials which have conductivity and resistivity inbetween conductors and insulators are called semiconductors.


## Energy Band Theory of Solids

According to Bohr's theory there are well defined energy levels of electrons in an atom. If large number of atoms are brought close to one another to form a crystal, they begin to influence each other. Due to this interatomic interaction there is no modification in the energy levels of the electrons in the outer shell but there is a considerable modification in the energy levels of the electrons in the outer shells.




To understand modification in energy levels of electrons consider a silicon crystal containing N atoms.

Silicon (si) atoms have four valance electrons i.e. number of electrons in the outermost orbit is 4. Therefore the total number of valence electrons in the crystal of si is 4N.

(i) If the interatomic spacing of the si atoms is very Large ($r = d$), then there is no interatomic interaction.

(ii) When the interatomic spacing $r$ is less than d but greater than c, then there is no visible spliting of energy levels.

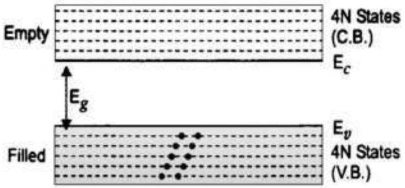
(iii) When the interatomic spacing $r$ is equal to c, the energy of outermost shell electrons of neighbouring silicon atoms start changing i.e. the spliting of these energy levels occurs. Whereas there is no change in the energy. levels of electrons in the inner shells.

(iv) When interatomic spacing $r$ lies inbetween b and c ($b < r < c$), instead of a single 3s or 3p level, we get a large number of closely packed levels. Where 2N levels corresponding to a single 3s level and 6N levels for a single 3p level of an isolated atom. This spreading of energy levels reduces the energy gap between 3s and 3p levels of free atom.

This collection of closely spaced levels is called an energy band.

(v) When the interatomic spacing $r$ becomes equal to b but greater than a ($r = b > a$), the energy gap between 3s and 3p levels completely disappears. In such a situation, it is not possible to distinguish between the electrons belonging to 3s and 3p subshells. We can only say that 4N levels are filled and 4N levels are empty.

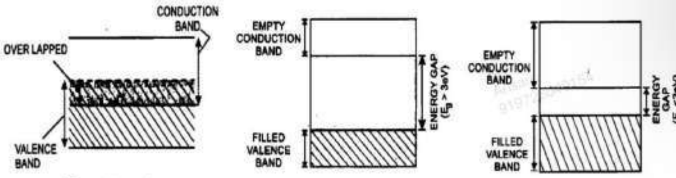
(vi) When the interatomic spacing r becomes equal to a (r = a) then the band of 4N filled energy levels is separated from the band of 4N unfilled energy levels by an energy gap called energy band gap, which is denoted by $E_g$.




The lower completely filled band is called valance band and the upper unfilled band is called conduction band. The minimum energy required for shifting electrons from valance band to conduction band is equal to energy band gap ($E_g$).

## Difference between Metals (Conductors), Insulators and semiconductors on the basis of Energy Bands

**Conductors (Metals)** In conductors the conduction and valance band partly overlap each other and there is no energy gab in between.




Conductors Insulators Semiconductors

## Semiconductors -

In semiconductors the valance band is totally filled and the conduction band is empty but the energy gap between conduction band and valance band is quite small. It is less than 3 ev. $E_g$ for germanium is 0.72 ev and for silicon it is 1.1 ev.

At zero kelvin temperature semiconductor behaves as insulator.

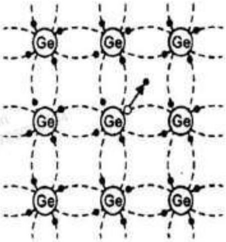
## Insulators -

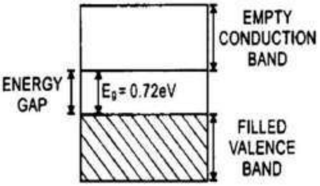
In insulators the energy gap is quite large ($E_g > 3$ ev). Due to Large energy gap no electron is able to go from the valance band to the conduction band. Hence electrical conduction in these materials is impossible and they behave as insulators.

# INTRINSIC SEMICONDUCTORS

A pure semiconductor which is free of every impurity is called intrinsic semiconductor.

Examples - Silicon (Si) and Germanium (Ge).




Silicon (14) $1s^2 2s^2 2p^6 3s^2 3p^2$

Germanium (32) $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

Both the atoms (Si and Ge) have four valance electrons.

The four valance electrons of a germanium atom form four covalent bands by sharing the electrons of neighbouring four germanium atoms.

The minimum energy required to break a covalent band is 0.72 ev for Ge and 1.1 ev for Si. At room temperature when an electron breaks away from a covalent bond, the empty place or vacancy left in the bond is called a hole.

When an external electric field is applied, these free electrons and holes move in opposite directions and constitute a current. The number of free electrons and holes are exactly equal in an intrinsic semiconductor.

$$n_e = n_h$$

Also the conductivity of intrinsic semiconductor is very low. The hole is considered as an active particle in the valance band, having a positive charge equal to that of an electron.

## Doping :-

Doping is a process of addition of a desirable impurity atoms to a pure semiconductor to modify its properties in a controlled manner. The impurity atoms added are called dopants.

Doping of a semiconductor increases its electrical conductivity to a great extent.

## Methods of doping

(i) Add the impurity atoms in the melt of semiconductor.

(ii) Implant dopant atoms by bombaring the semiconductor with their ions.

(iii) Heat the semiconductor in atmasphere of dopant atoms.

[redacted]

# EXTRINSIC SEMICONDUCTORS

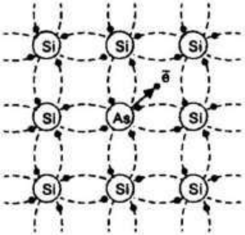
A doped semiconductor or a semiconductor with suitable impurity atom added to it is called extrinsic semiconductor.

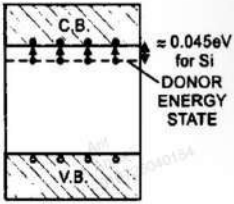
## (i) n-type Semiconductor

When a pure semiconductor of silicon (Si) or Germenium (Ge) is doped with pentavalent atoms which have five valance electrons (Phosphorous, Arsenic, antimony or Bismuth) then it is called n-type semiconductor.

The four of the five valance electrons of the impurity atoms will form covalent band with the adjoining four atoms of the silicon, while the fifth electron is free to move. Thus each impurity atom added donotes one free electron to the crystal. These impurity atoms are called donor atoms.

Since the conduction of electricity is due to the motion of electrons (i.e. negative charges), so that the resulting semiconductor is called n-tye or donor type semiconductor.



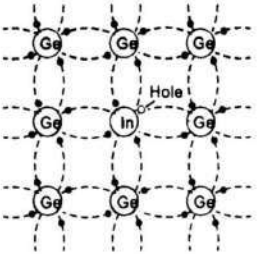



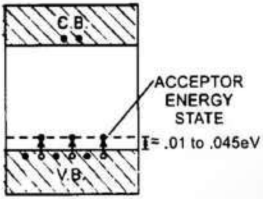

In n-type semiconductors electrons are majority carriers and holes are minority carriers.

## (ii) P-type Semiconductor –

When a pure semiconductor of silicon (Si) or Germanium (Ge) is doped with a controlled amount of trivalent atoms, which have three valance electrons (Boron, Aluminium, Gallium, Indium) then it is called p-type semiconductor.

The three valance electrons of the impurity atom will form covalent bonds with the adjoining three atoms of germanium (Ge), while there will be one incomplete covalent bond with a neighbouring Ge atom, this deficiency of an electron creates a 'hole'.




The trivalent atoms are called acceptor atoms and the conduction of electricity occurs due to motion of holes (i.e. positive charges), so the resulting semiconductor is called p-type or acceptor type semiconductor.

In p-type semiconductor electrons are minority carriers and holes are majority carriers.

| Intrinsic Semiconductors | Extrinsic Semiconductors |
|---|---|
| Semiconductor in its purest form. | Semiconductor in its impure form. |
| It has low conductivity. | It has a higher conductivity than an intrinsic semiconductor |
| The band gap between the conduction and valence bands is quite narrow. | The energy gap is greater than that of an intrinsic semiconductor. |
| Fermi level can be found in the forbidden energy gap. | The presence of a Fermi level depends on the type of extrinsic semiconductor. |
| Temperature alone determines electrical conductivity. | Electrical conductivity in a pure semiconductor is affected by temperature as well as the quantity of impurity doping. |
| Pure Silicon and Germanium crystalline forms are examples. | Impurities such as As, Sb, P, In, Bi, Al, and others are doped with Germanium and Silicon atoms. |

| N-type semiconductors | P-type semiconductors |
|---|---|
| N-type semiconductor is obtained by doping and intrinsic semiconductor with pentavalent impurity. | P-type semiconductor is obtained by doping and intrinsic semiconductor with trivalent impurity. |
| Here electrons are majority carriers and holes are minority carriers. | Here holes are majority carriers and electrons are minority carriers |
| It has donor energy levels very close to CB | It has acceptor energy levels very close to VB. |
| When the temperature is increased, these semiconductors can easily donate an electron from donor energy level to the CB | When the temperature is increased, these semiconductors can easily accept an electron from VB to donor energy level . |

# P-N JUNCTION

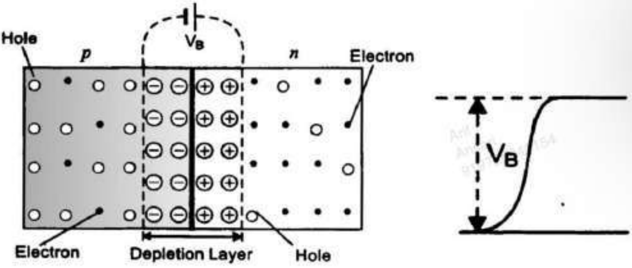
When a p-type semiconductor crystal is joined with an n-type semiconductor crystal, then the resulting arrangement is called a p-n junction or junction diode.

## Formation of PN-Junction –

To make a p-n junction, the n type and p-type silicon crystals are cut into thin wafers. If on a wafer of n-type silicon, an aluminium film is placed and heated to a high temperature 580°c, aluminium diffuses into silicon and a p-type semiconductor is formed on an n-type semiconductor. Such a formation of p-region on n-region is called p-n junction.

## Diffusion and Drift –

When p-n junction is formed due to difference in concentration of charge carriers in two regions of p-n junction, the electrons from n-region diffuse through the junction into p-region and holes from p-region diffuse into n-region. The motion of charge carriers gives rise to diffusion current across the junction.



Due to diffusion of electrons and holes a layer of positively charged donor atoms in n-region and a layer of negatively charged acceptor atoms in p-region are created. This positive and negative space charge regions on both sides of p-n junction will form a region which has immobile ions and is called depletion region.

Due to positive and negative space charge region at p-n junction, an electric field is set up across the junction. Due to this electric field developed at the junction, an electron on p-side of the junction moves to n-side and a holes on n-side of junction moves to p-side of junction.

The motion of these charge carriers due to electric field is called drift. As a result of it, a drift current starts, which is opposite in direction to the diffusion current.

In the begining the diffusion current is large but drift current is small. As the diffusion process continues, the strength of electric field across the junction increases and thereby drift current increases. This process continues until the diffusion current becomes equal to the drift current. Now the p-n junction is said to be be in equilibrium state and there is no current across the p-n junction.

At this stage, the potential barrier across the junction has maximum value $V_B$. Now the movement of majority charge carries across the junction stops and the potential acts as a barrier, hence known as potential barrier.

At room temperature (300 K) $V_B$ is about 0.3 V for Ge and 0.7 V for Si. The value of $V_B$ increases with rise in temperature for Ge and Si.

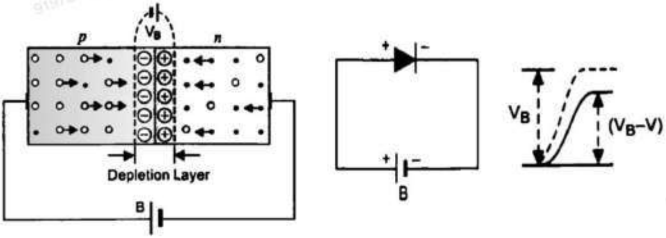
# BIASING OF PN JUNCTION -

There are two methods of biasing the p-n junction-

(i) Forward biasing (ii) Reverse biasing

## (1) Forward Biasing :-

A p-n junction is said to be forward biased if the positive terminal of the external battery is connected to p-side and the negative terminal to the n-side of p-n junction.



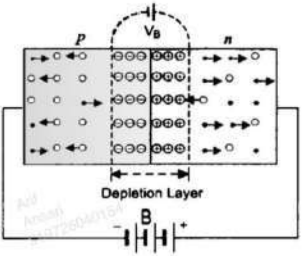

In forward biasing the forward voltage opposes the potential barrier $V_B$. As a result of it potential barrier and width of depletion layer decreases. The effective value of potential barrier in forward biasing is $(V_B - V)$.

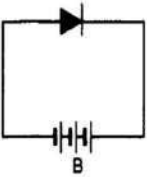
## (2) Reverse Biasing :-

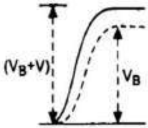
A p-n junction is said to be reverse biased if the positive terminal of the external battery is connected to n-side and the negative terminal to p-side of the p-n junction.

In reverse biasing the reverse bias voltage supports the potententential barrier $V_B$. As a result of it barrier potential and width of depletion region increases.

The effective value of barrier potential under reverse bias is $(V_B + V)$.



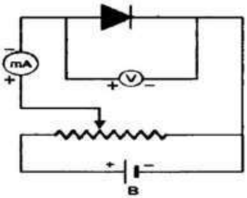



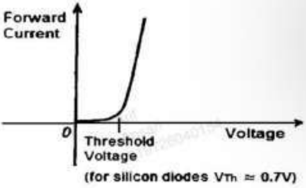

In reverse biasing, there is no conduction across the junction due to majority carriers. However a few minority carriers of p-n junction diode cross the junction after being accelerated by high reverse bias voltage. They constitute a current which is called reverse current or leakage current.

## CHARACTERISTICS OF PN JUNCTION DIODE

### (i) Forward Characteristics -

On plotting a graph between forward bias voltage and forward current we get the following graph.

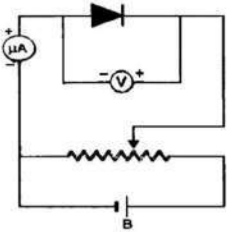


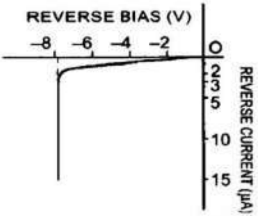




It is found that beyond forward voltage $V = V_K$, called knee voltage (0·3 V for Ge and 0·7 V for Si) the current through the junction starts increasing rapidly with voltage and showing the linear variation. But below the Knee voltage the variation in current is negligible and the curve is non-linear.

## (ii) Reverse Characteristics -

On plotting a graph between reverse bias voltage and reverse current, we get the reverse characteristics as shown in fig. From the curve we note that in reverse biasing of p-n junction, the current is very small (≈ μA) and is independent on voltage upto certain reverse bias voltage, Known as breakdown voltage.




If the reverse bias voltage exceeds the breakdown voltage, the reverse current through the p-n junction will increase abruptly. If this current exceeds the rated value of p-n junction (specified by manufacturer), the p-n junction will get damaged.

# PN-DIODE AS A RECTIFIER

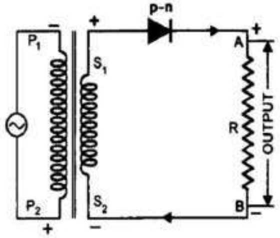
Rectifier is a device which is used for converting alternating current/voltage into direct current/voltage.

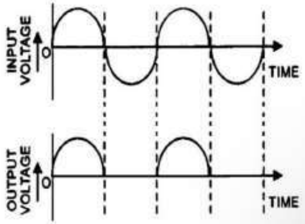
There are two types of rectifier -

(i) Half wave rectifier (ii) Full Wave Rectifier

## (1) HALF WAVE RECTIFIER -

A.C. voltage to be rectified is connected to the primary winding $P_1P_2$ of a stepdown transformer. $S_1S_2$ is the secondary coil of the transformer. $S_1$ is connected to the portion P of the p-n junction. $S_2$ is connected to the portion n through Load resistance R. Output is taken across the Load resistance R.




### WORKING -

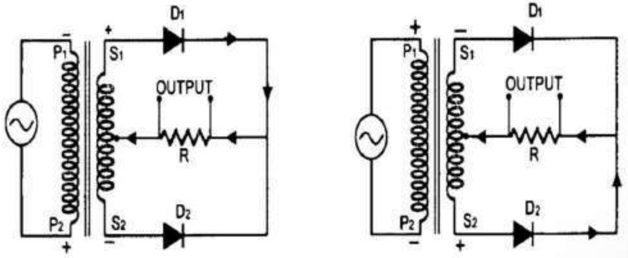
During positive half cycle of A.C., suppose $S_1$ becomes positive, $S_2$ becomes negative and the p-n junction is forward biased. The resistance of pn junction becomes Low. The maximum forward current flows in the circuit and we get output across-Load.

During negative half cycle of A.C. $S_1$ becomes negative and $S_2$ is positive. The p-n junction is reverse biased. It offers high resistance and hence there is no flow of current and thus no output across Load.

Hence in the output, we have current corresponding to one half cycle of the wave and the other half is missing. That is why the process is called half wave rectification.

## (2) FULL WAVE RECTIFIER –

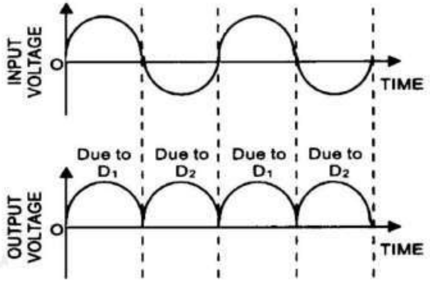
For full wave rectification, we have to use two p-n junction diodes $D_1$ and $D_2$. The circuit is shown in the given fig.




**WORKING –**

During the positive half cycle of A.C. the diode $D_1$ is forward biased and the diode $D_2$ is reverse biased. The forward current flows through diode $D_1$ in the direction as shown in fig.

During the negative half cycle of A.C. the diode $D_1$ is reverse biased and the diode $D_2$ is forward biased. The forward current flows through diode $D_2$. We observe that during both the half cycles of A.C., current through R flows in the same direction.




Hence the output signal voltage is unidirectional having ripple contents (i.e. d.c. components and a.c. components of voltage). It can be converted into d.c. voltage by filtering through a filter circuit.

***Q.1. The energy gap of germanium is 1.28 eV. What is the maximum wavelength at which germanium will begin absorbing energy.***

***Solution:*** Using $\frac{hc}{\lambda} = E$

$$\therefore \lambda = \frac{hc}{E} = \frac{6.628 \times 10^{-34} \times 3 \times 10^{8}}{1.28 \times 1.6 \times 10^{-19}} m$$

$$= 12.33 \times 10^{-7} m$$

***Q.2. Pure Si at 400K has equal electron ($n_e$) and hole ($n_h$) concentrations of $3 \times 10^{16} m^{-3}$. Doping by indium, $n_h$ increases to $6 \times 10^{22} m^{-3}$. Calculate $n_e$ in the doped Si.***

**Solution:** In thermal equilibrium, $n_e n_h = n_i^2$;

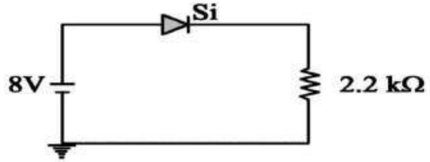
$$\therefore n_e = \frac{n_i^2}{n_h} = \frac{\left(3 \times 10^{16}\right)^2}{6 \times 10^{22}}$$

$$= 1.5 \times 10^{10} m^{-3}$$

***Q.3. Why Carbon acts as insulator while Silicon and Germanium act as semiconductors?***

***Solution :*** The four bonding electrons of carbon, silicon and germanium are present in the second, third and fourth orbit. It results in the comparatively higher ionization energy for carbon and least for Germanium. Hence, the number of free electrons responsible for conduction is significantly more in Germanium and silicon as compared to Carbon.

**Q.4. *Find voltage across resistor, across diode and current through diode.***



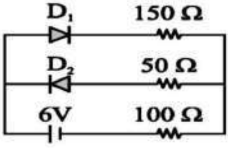

**Solution:** $V_D = 0.7V$

$$\therefore \quad V_R = 8V - 0.7V = 7.3V$$

$$\therefore \quad i_R = i_D = \frac{7.3}{2.2 \times 10^3}$$

$$= 3.31 \times 10^{-3} A$$

**Q.5. *If each diode forward resistance is 50 Ω then find current through the 100 Ω resistor in the given circuit.***

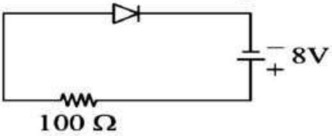



***Solution:*** The diode $D_1$ is forward biased but diode $D_2$ is reverse biased. So no current pass through the diode $D_2$.

$\therefore$ Current passes through 100 Ω resistor

$$= \frac{6}{150 + 100} = 0.02A$$

***Q.6. A source voltage of 8V drives the diode in fig. through a current-limiting resistor of 100 ohm. Then the magnitude of the slope of load line on the V-I characteristics of the diode is***




**Solution:**

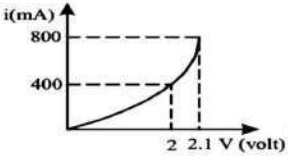
If I is the current in the diode and V is voltage drop across it, then for given figure, voltage equation is:

$$(I\times 100) - V = 8$$

$I = (1/100)V + 8/100 = (0.01)V + 0.08$

Thus the slope of I-V graph is equal to $1/R_L = 0.01$

***Q.7. The I-V characteristic of a P-N junction diode is shown below. The approximate dynamic resistance of the P-N junction when a forward bias of 2volt is applied is***



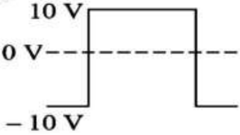

**Solution:**

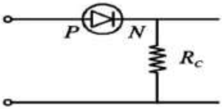
The current at 2V is 400 mA and at 2.1 V it is 800 mA. The dynamic resistance in this region

$$R = \frac{\Delta V}{\Delta i}$$

$$= \frac{(2.1-2)}{(800-400)\times 10^{-3}} = 0.25\Omega$$

***Q.8. If the following input signal is sent through a PN-junction diode, then the output signal across $R_L$ will be***




***Solution:*** When input voltage is -10 V, the diode is reverse biased and no output is obtained. On the other hand, when input is +10V, the diode is forward biased and output is obtained which is +10V. Therefore the output is of the form as shown in the following figure