p-n Junction

Objectives

After going through this module, the learners will be able to:

- Understand the formation of *p-n* junction
- Explain Junction barrier
- Explore Forward characteristics and Reverse characteristics
- Define Dynamic resistance and obtain its expression

Content Outline

- Unit Syllabus
- Module Wise Distribution of Unit Syllabus
- Words You Must Know
- Introduction
- *p-n* Junction
- Biasing of a *p-n* Junction Diode
- Characteristics of a *p-n* Junction Diode
- Dynamic Resistance of The Junction Diode
- Summary

Unit Syllabus

Unit 9: Electronic Devices

Chapter 14: semiconductor electronic material, devices and simple circuits.

Energy bands in conductors, semiconductors and insulators (qualitative only) semiconductors intrinsic and extrinsic

Semiconductor diode -IV characteristics in forward and reverse bias, application of diode as a rectifier

Special purpose p-n diodes LED, photodiode, solar cell and Zener diode and their characteristics, Zener diode as a voltage regulator

Junction transistor, transistor action, characteristics of a transistor and transistor as amplifier common emitter configuration

Basic idea of analog and digital signal, logic gates OR, AND, NOR, NOT, NAND logic gates, truth table

Keeping the needs of state boards in mind we have not changed the content

Module Wise Distribution of Unit Syllabus - 10 Modules

Module 1	• Energy bands in solids • Forbidden gap • Fermi level • Energy bands in conductors, semiconductors and insulators
Module 2	• Uniqueness of semiconductors • Charge carriers in semiconductors electrons and holes • Intrinsic semiconductors • Extrinsic semiconductors p and n type • Why are p and n type semiconductors neutral?
Module 3	• p-n junction diode • Potential barrier • Depletion layer • Characteristics of p-n junction diode • Forward and reverse bias, knee voltage, magnitude of bias voltages • To draw the IV characteristics curve for a p-n junction in forward bias and reverse bias

Module 4	• Application of diode
	• Rectifier meaning and need of such a devise
	• Half wave and full wave rectifier
	• Rectifier in our homes
	• Special purpose diode
	  ○ LED
	  ○ Photodiode
	  ○ Solar cells
	• Solar panels and future of energy

Module 5	• To identify a diode, a LED, a resistor and a capacitor • Use a multimeter to

	○ *See the unidirectional flow of current in case of a diode and an LED* ○ *Check whether a given diode is in working order*
Module 6	● Zener diode ● Characteristics of Zener diode ● To draw the characteristic curve of a Zener diode and to determine its reverse breakdown voltage ● How is a Zener diode different from other diodes? ● Zener diode as a voltage regulator ● Working of a Zener diode ● Zener diodes in our homes
Module 7	● Junction transistor ● design of the transistor ● *n-p-n* and *p-n-p* ● Use a multimeter to ○ *Identify base of transistor* ○ *Distinguish between n-p-n and p-n-p type transistor* ○ *Check whether a given electronic component* (e.g. diode, transistor, or IC) is in working order ● Transistor action ● Characteristics of a transistor, n-p-n common emitter
Module 8	● Understanding transistor characteristics and its applications ● To study the characteristics of a common emitter n-p-n and p-n-p transistor and to find the values of current and voltage gains. ● Transistor as switch ● Transistor as amplifier
Module 9	● Transistor as an amplifier ● Circuit diagram and understanding bias ● Input and output waveforms ● Phase change
Module 10	● Analog signals

	• Logic gates • Truth tables • OR gate • AND gate • NOT gate • NAND gate • NOR gate

Module 3

Words You Must Know

- **Conductors:** These are the materials which conduct electricity easily. They have a very large number of free electrons.
- **Insulators: These** are the materials which do not conduct electricity because they do not have free electrons.
- **Semiconductors: These** are the materials for which electrical conductivity value is less than conductors but more than insulators. The conductivities of semiconductors are highly temperature sensitive.
- **Energy Level:** As per Bohr's theory electrons revolve around the nucleus only in some specific orbits called stationary orbits. Energy of electrons in these orbits is constant. These orbits are termed as energy levels.
- **Valence Bands:** This band comprises energy of valence electrons. Electrons of this band do not contribute to conduction of electric current.
- **Conduction Band:** This band corresponds to energy of free electrons. Electrons of this band are responsible for conduction of electric current.
- **Forbidden Energy Gap (E_g):** It is the minimum energy required to take an electron from valence band to conduction band. Insulators have highest E_g and conductors have least Eg.
- **Intrinsic Semiconductors:** These are pure semiconductors without any impurity. They show very small electrical conductivity at room temperature.
- **Doping:** It is the deliberate and controlled addition of impurities in intrinsic semiconductors to enhance their electrical conductivity in a controlled manner.
- **Extrinsic Semiconductors:** Semiconductors to which impurities are added to increase conductivity are known as extrinsic semiconductors or impurity semiconductors

- **Dopant:** Two types of dopants used in doping the tetravalent Si or Ge element:
    i. Pentavalent dopants (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.
    ii. Trivalent dopants (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.
- ***p*-type Semiconductors:** These are formed by doping elements like Si and Ge with trivalent atoms.
- ***n*-type Semiconductors:** These are formed by doping elements like Si and Ge with pentavalent atoms.

Introduction

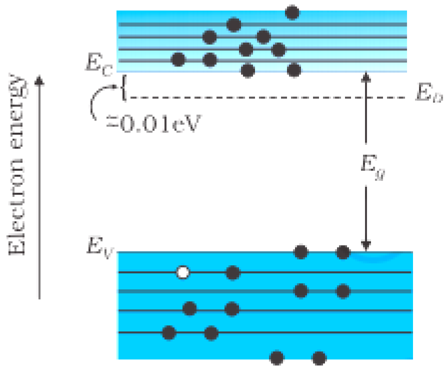
We have learnt that the energy bands formation in bulk materials helped us to imagine the solids being classified as conductors and insulators. The energy bands corresponding to the outermost orbits of electrons were called valence bands. The next higher energy states which the electron could occupy were labelled as conduction bands. This classification helps describe a class of solids called semiconductors. These materials were insulators at very low temperatures, but could conduct reasonably well at room temperature**.** The conduction in metals (conductors) was due to electrons as we have considered in our previous courses on electricity.

Vacancy Election

- The concept of holes is corresponding to vacancies created by electrons moving to the conduction band in semiconductors. This vacancy of electron in the valence band is called a hole. The vacancy (hole) moves in the valence band, as electrons in valence band try and fill the positive space created, and creating a vacancy in another place.
    - In extrinsic semiconductors, because of the abundance of majority current carriers, the minority carriers produced thermally have more chance of meeting majority carriers and thus getting annihilated or neutralised. Hence, the dopant, by adding a large number of current carriers of one type, which become the majority carriers, indirectly helps to reduce the intrinsic concentration of minority carriers.
    - The semiconductor's energy band structure is affected by doping. In the case of extrinsic semiconductors, additional energy states due to donor impurities (E_D) and acceptor impurities (E_A) also exist.

AS we have considered in the previous module

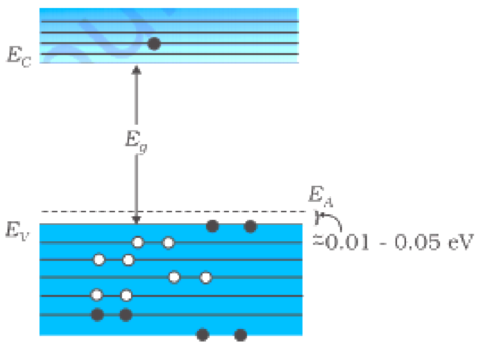
- In the energy band diagram of n-type Si semiconductor, the donor energy level E_D is slightly below the bottom E_C of the conduction band and electrons from this level move into the conduction band with a very small supply of energy.



(a) $T > 0K$

n-Type Semiconductor at T > 0K

- At room temperature, most of the donor atoms get ionised but very few ($\sim10^{-12}$) atoms of Si get ionised. So the conduction band will have most electrons coming from the donor impurities,
- Similarly, for p-type semiconductor, the acceptor energy level E_A is slightly above the top E_V of the valence band. With a very small supply of energy an electron from the valence band can jump to the level E_A and ionise the acceptor negatively. (Alternatively, we can also say that with a very small supply of energy the hole from level E_A sinks down into the valence band.



(b) $T > 0K$

- Electrons rise up and holes fall down when they gain external energy.) At room temperature, most of the acceptor atoms get ionised leaving holes in the valence band.

Thus at room temperature the density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor.

The electron and hole concentration in a semiconductor in thermal equilibrium is given by

$n_e n_h = n_i^2$

Though the above description is grossly approximate and hypothetical, it helps in understanding the difference between metals, insulators and semiconductors (extrinsic and intrinsic) in a simple manner.

- **The difference in the resistivity of C, Si and Ge depends upon the energy gap between their conduction and valence bands.**
- **For C (diamond), Si and Ge, the energy gaps are 5.4eV, 1.1eV and 0.7eV, respectively.**
- **Sn also is a group IV element but it is a metal because the energy gap in its case is 0 eV.**

What is likely to happen, if p-type and n-type semiconductors are combined?

Would the majority carriers in n-type neutralise the majority carriers in p-type semiconductors?

Let us now try to understand this situation

p-n **Junction**

- A *p-n* junction is a boundary or interface between the two types of semiconductors, (*p*-type and *n*-type), inside a single crystal.
- A p-n junction is formed when a semiconductor material, like silicon or germanium, is doped with an acceptor impurity on one side and a donor impurity on the other side.
- The p-side contains excess holes and the n-type contains excess electrons in the outer shells of electrically neutral atoms.
- This allows the electrical current to pass through the junction only in one direction. The junction is grown on a single crystal and not on two separate pieces that have been joined together.
- To form a p-n junction, the semiconductor is first doped with, say, donor impurity to make the entire crystal n type. This is then further doped with p type impurity from one side, in higher concentration, to make that side p type. Now the crystal has, say,

on the left hand side p-type impurity and on the right hand side n-type impurity. This forms the respective p- side and n- side of the junction diode.

Consider a Thin p-Type Silicon

- (p-Si) semiconductor wafer. By adding precisely, a small quantity of pentavalent impurity, part of the p-Si wafer can be converted into n-Si. There are several processes by which a semiconductor junction can be formed. The wafer now contains p-regions and n-regions and a metallurgical junction in between p- and n- regions.

Two important processes occur during the formation of a p-n junction:

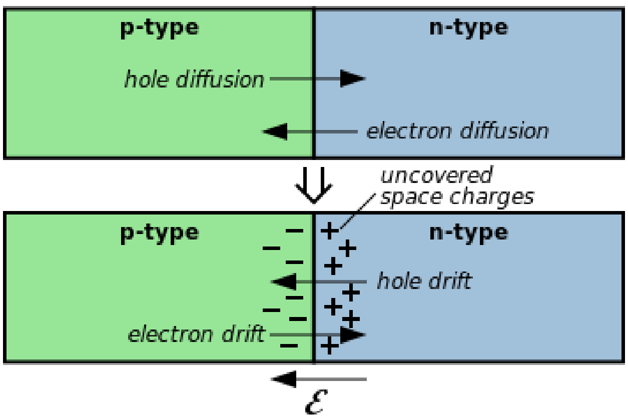
- **Diffusion**
- **Drift**

Cause of Diffusion Current

We know that in an n-type semiconductor, the concentration of electrons (number of electrons per unit volume) is more compared to the concentration of holes. Similarly, in a p-type semiconductor, the concentration of holes is more than the concentration of electrons. During the formation of the p-n junction, and due to the concentration gradient across p –side and n - sides,

Holes diffuse from p-side to n-side (p → n) and electrons diffuse from n-side to p-side (n → p).

This motion of charge carries gives rise to **diffusion current** across the junction.



https://upload.wikimedia.org/wikipedia/commons/thumb/3/3e/Pn_Junction_Diffusion_and_Drift.svg/375px-Pn_Junction_Diffusion_and_Drift.svg.png

What is the result of diffusion current?

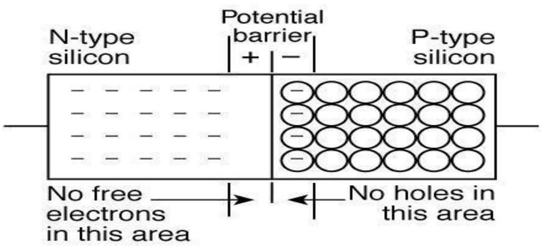
Now in this situation, things are not in equilibrium as there is a higher concentration of holes on the left side and a lower concentration of holes on the right side. Similarly, the concentration of electrons on the right side is more than the concentration of electrons on the left side.

This leads to **diffusion of electrons from right of junction to left side** and similarly **the holes from the left diffuse to the right**. This leads to a **diffusion current from p-side to n-side.**

Initially both the sides were electrically neutral. Now, because of diffusion of electrons and the holes, there are immobilised additional ions on both the sides.

From the n-side, electrons have diffused to p-side, so there are positive immobile ions on the n-side, from the p-side, holes have diffused to the n-side, so there are negative immobile ions on the p-side. These immobile ions near the junction create a potential difference across the junction.

This potential difference is called potential barrier.



The physical distance from one side of the barrier to the other is known as the width of the barrier and the potential difference between the two sides is known as the **height of the barrier**.

Symbolically potential across the junction is represented by V_b.Due to the presence of V_b across the junction an electron would require energy of V_b to cross the junction.Same amount of energy will be required by the hole to move from p-side to n-side.

At room temperature the value of V_b for Ge is 0.3V and for Si it is 0.7V.

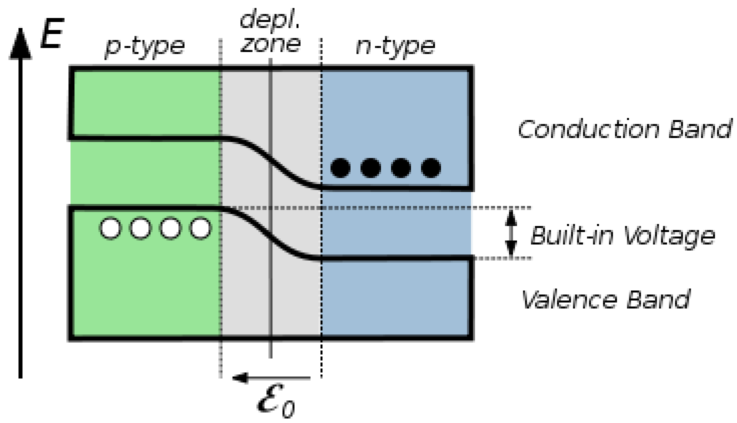
The width and the magnitude of barrier potential depends on

- **The nature of the semiconductor and**
- **The extent of doping**

If the doping concentration is more, then the width of the junction will be small and the resulting junction field would therefore become large.

Cause of Drift Current

- When an electron diffuses from n → p, it leaves behind an ionised donor on the n-side.
- This ionised donor (positive charge) is immobile as it is bonded to the surrounding atoms.
- As the electrons continue to diffuse from n → p, a layer of positive charge (or positive space-charge region) on the n-side of the junction is developed.
- Similarly, when a hole diffuses from p → n due to the concentration gradient, it leaves behind an ionised acceptor (negative charge) which is immobile. As the holes continue to diffuse, a layer of negative charge (or negative space-charge region) on the p-side of the junction is developed.
- This space-charge region on either side of the junction together is known as depletion region as the electrons and holes taking part in the initial movement across the junction depleted the region of its free charges



https://upload.wikimedia.org/wikipedia/commons/thumb/6/63/Un-Biased_pn_Junction_Bands.svg/400px-Un-Biased_pn_Junction_Bands.svg.png

Notice the cause of potential difference between the p and n-type sides of the semiconductor. The thickness of the depletion region is of the order of one-tenth of a micrometre.

Due to the positive space-charge region on the n-side of the junction, and negative space-charge region on the p-side of the junction, an electric field, directed from positive charge towards negative charge develops.

Due to this field, an electron on the *p*-side of the junction moves to the *n*-side and a hole on the *n*-side of the junction moves to *p*-side. The motion of charge carriers due to the electric field is called drift.

Thus a drift current, which is opposite in direction to the diffusion current is set up.

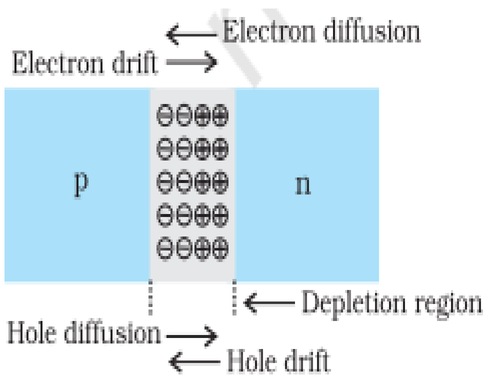
We have already noticed that the region near the junction, which has immobile ions and is deprived of any charge carriers, is called the **depletion region or the depletion layer**.

This layer has a potential difference across it that makes it difficult for the electrons and holes to diffuse to the other side; however there can be few charge carriers which have sufficient energy to cross over to the other side. This amounts to the diffusion current across the junction. So the electrons from the n side, diffusing to the p side forms a small amount of current across the junction known as **diffusion current**.

We thus see that an important phenomenon that takes place during the formation of a p-n junction is diffusion. There is another important phenomenon that takes place during its formation; this phenomenon is drift of charge carriers.

Due to the potential difference across the junction and thermal collisions, there are electron hole pairs which are generated in the junction, but they are immediately forced to move out of the junction because of the potential difference across the junction. This leads to electrons drifting towards the n-type and holes drifting towards the p-type semiconductor. This leads to a small drift current from n-side to p-side.

The figure shows the direction of electron diffusion and electron driftIt also shows the direction of hole diffusion and hole drift



The direction of the drift current is opposite to that of the diffusion current.

Do You Think

The electron and hole movements should just continue and negate the doping in p and n Si wafers? If so, why is the real situation different?

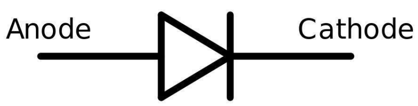
Initially the diffusion current is more as there is quite a lot of concentration difference. As the potential barrier grows, the diffusion current reduces and the drift current increases. This continues till diffusion current becomes equal to the drift current in magnitude and there is no net transfer of charge across the junction.This state is known as **equilibrium or steady state.** It is in this steady state that we receive our practically formed p-n junction diodes.

Can we take one slab of p-type semiconductor and physically join it to another n-type semiconductor to get a *p-n* junction?

No! Any slab, however flat, will have roughness much larger than the interatomic crystal spacing (~2 to 3 Å) and hence continuous contact at the atomic level will not be possible. Such a p-n junction will behave as a discontinuity for the flowing charge carriers.

Biasing of a p-n Junction Diode

Any device which allows the current to flow freely in one direction but doesn't allow it to flow in the opposite direction is called a diode. Thus a p-n junction is also called a p-n junction diode. The symbol of a diode is



https://en.m.wikipedia.org/wiki/Diode

We have already discussed that in the steady state, net current across the junction is zero. Now let us try to see what happens when a battery is connected across a p-n junction diode.

Bias as we know is a prejudice in favour of or against something.Here it means placing an external potential difference for the special purpose of getting or stopping a current across a p-n junction.

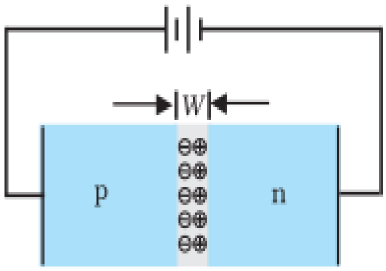
There are **two possibilities with the use of an external battery**,

Let us study them one by one.

In the simplest case no external battery connected across the diode. It is **unbiased**. In this condition the diode is in equilibrium. There is a junction barrier across which there is a potential difference and the n-side is at higher potential than the p-side. It is this potential difference which stops further diffusion of electrons.

Forward Biasing

The first case is that the diode is connected with a battery across it. The battery has its positive terminal connected to the p-side of the diode and its negative terminal connected to the n-side of the diode. This is shown in the figure: -



When an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal it is said to be forward biased.

The applied voltage drops mostly across the depletion region and the voltage drop across the p-side and n-side of the junction is negligible. (This is because the resistance of the depletion region – a region where there are no charges – is very high compared to the resistance of the *n*-side and p-side.)

The direction of the applied voltage (V) is opposite to that of the built-in potential barrier V_d. As a result, the depletion layer width decreases and the barrier height is reduced. The effective barrier height under forward bias is $(V_d – V)$.

If the applied voltage is small, the barrier potential will be reduced only slightly below the equilibrium value, and only a small number of carriers in the material—those that happen to be in the uppermost energy levels will possess enough energy to cross the junction.

So the current will be small.

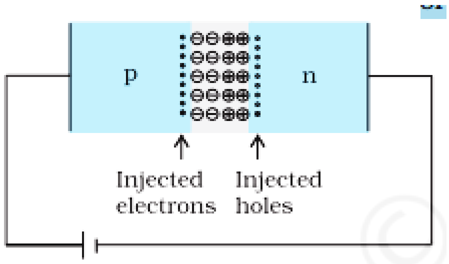
If we increase the applied voltage significantly, the barrier height will be reduced and more carriers will have the required energy.

Thus the current increases.

Due to the applied voltage, electrons from n-side cross the depletion region and reach p-side (where they are minority carriers).Similarly, holes from p-side cross the junction and reach the n-side (where they are minority carriers).

This process under forward bias is known as minority carrier injection. At the junction boundary, on each side, the minority carrier concentration increases significantly compared to the locations far from the junction.

Due to this concentration gradient, the injected electrons on p-side diffuse from the junction edge of p-side to the other end of p-side. Likewise, the injected holes on the *n*-side diffuse from the junction edge of *n*-side to the other end of *n*-side.

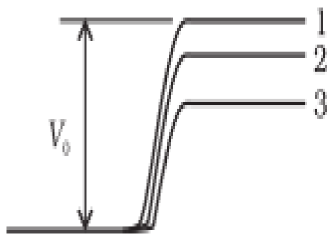


The battery is connected in such a way that the positive terminal of the battery is connected to the p-side of the diode and negative terminal is connected to the n-side of the diode. This way the diode is said to be in Forward bias.

This motion of charged carriers on either side gives rise to current. The total diode forward current is the sum of hole diffusion current and conventional current due to electron diffusion.

The magnitude of this current is usually in the order of mA.

In forward biasing the height of the potential barrier decreases as the potential of the *n*-side is reduced by the negative terminal of the battery.



Barrier potential (1) without battery, (2) Low battery voltage, and (3) High voltage battery. This leads to more number of electrons diffusing from n-side to the p-side

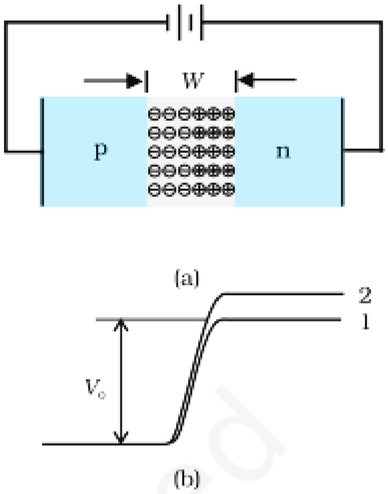
Hence Forward bias results in

- **When an external potential difference is applied in the forward bias mode,**
- **The (forward bias) external potential is in the opposite direction of the barrier potential this result in decrease in the potential barrier height and width.**

- **The depletion layer decreases and the electrons in the n-side are repelled by the negative terminal of the battery and they gain energy and are able to cross the junction to reach the p-side.**
- **Thus during forward biasing, the diode conducts electricity and for every recombination of electrons with holes, there is a new electron hole pair that is generated at the terminals of the battery.**
- **Thus a continuous current flows across the junction. The resistance, offered by diodes, is very low when it is in the forward bias condition.**

Reverse Biasing

The second option of connecting a diode with a battery is as shown in the figure.



The positive terminal of the battery is connected to the n-side of the semiconductor and the negative terminal is connected to the p-side. This way of connecting a diode with a battery is called Reverse Biasing.

The effects of reverse bias are listed here

- The battery further increases the potential of the n-side of the semiconductor and hence the potential barrier increases in both its height and its width.
- The electrons in the n region get attracted towards the positive terminal and the holes in the p region move toward the negative terminal of the battery.

- The width of the depletion layer increases and diffusion becomes more difficult, but due to the high reverse bias potential some minority carriers cross the junction after being accelerated.
- This is the drift current which remains almost unaffected when the diffusion current is reducing. Hence drift current exceeds the diffusion current here.
- Thus there is a net current from n to p-side. This net current is very small, typically in micro-amperes.

  Since the large increase in the reverse voltage shows small increase in the reverse current,

The resistance of the p-n junction diode is high in the reverse biasing

Example

Why does the width of the depletion layer of a p-n junction increase in reverse biasing?

Solution

During reverse biasing the positive terminal of the external battery attracts electrons from the n- region and its negative terminal attracts holes from the p- region that is majority charge carriers move away from the junction, this increases the width of the depletion layer.

Example

Can we measure the potential difference across an unbiased p-n junction by connecting a sensitive voltmeter across its terminals?

Solution

No, there are no free charge carriers in the depletion region of the p-n junction, therefore, offers infinite resistance in the absence of external battery

Example

Why is a p-n junction also called a junction diode?

Solution

A p-n junction allows a large amount to flow through it when forward biased and it offers a high resistance when it is reverse biased. This unidirectional property is similar to that of a vacuum diode. Hence the p-n junction diode is also called junction diode.

Example

Why does a potential barrier set up across a junction diode?

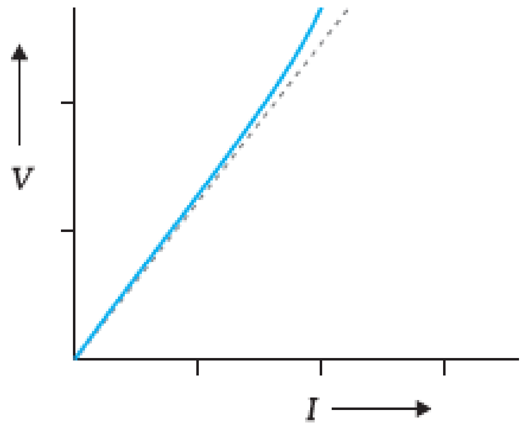
Solution

The accumulation of negative charges in the p region and the positive charges in the n region set up a potential difference across the junction. This is called a potential barrier which opposes the diffusion of electrons and hole across the junction.

Characteristics of a p-n Junction Diode

When a bias is placed across a conductor, its characteristic curves show the dependence of current on voltage placed across the conductor.

The simplest I-V curve is that of an ohmic resistor. According to Ohm's Law exhibits a linear relationship between the applied voltage and the resulting electric current; The current is proportional to the voltage, so the I-V curve is a straight line, with a positive slope passing through the origin.



Similarly, **the quantitative plot of current vs. potential difference is known as I-V characteristics of a p-n junction.**

The behaviour of p-n junction is different during its forward and its reverse bias

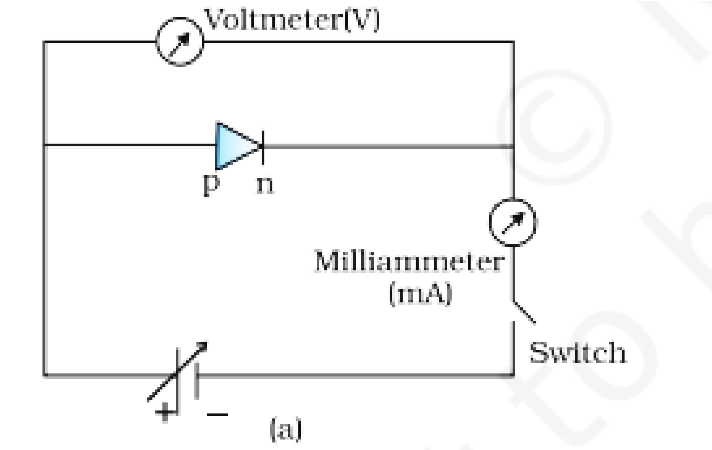
We can plot two types of characteristics, namely,

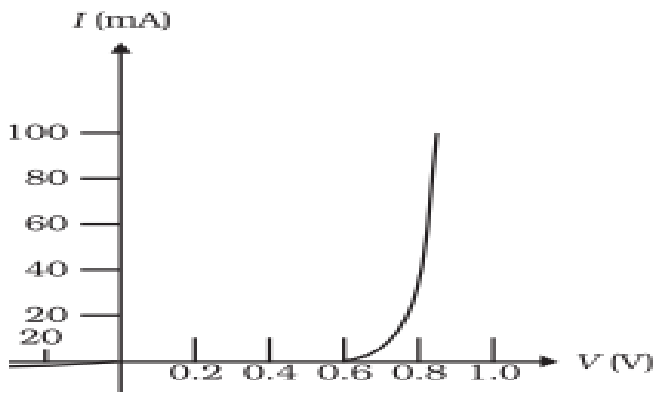
- **Forward Bias characteristics and**
- **Reverse Bias characteristics**

Forward Bias Characteristics

Forward characteristics are a plot between forward bias voltage applied across the diode and the forward current.

- Make connections as shown in the circuit. For a given forward bias voltage (in Volts) note the value of the forward current (in milli-amperes).
- With the help of the rheostat change the forward bias voltage and note the corresponding forward current reading.
- Now plot the graph between the forward current and the forward potential. The graph is shown below:





It can be seen from the graph,

- Initially till 0.7V (for Si and 0.3 for Ge) there is almost negligible forward current,
- Beyond this value the current increases rapidly with increase in forward potential.
- The special value of forward voltage beyond which the current increases with increase in the voltage is known as the knee Voltage.

Why does the diode not conduct before the Knee Voltage?

- The reason behind this behaviour is that even in the forward bias the diode needs to overcome the barrier potential. It is only when that is done, it begins to conduct.

- If the forward potential is increased beyond the specified safe limits, an extremely large current will be produced which will heat up the diode and can even damage it permanently due to overheating.

Example

Study the data given for forward bias characteristics

S n	Voltage across the diode (V)	Current in the circuit (mA)
1	0.05	0
2	9.91	0
3	0.15	0
4	0.20	0
5	9.25	0
6	0.30	0
7	0.35	0
8	0.40	0
9	0.45	0
10	0.50	0
11	0.55	0
12	0.60	0
13	0.65	10
14	0..70	30
15	0.75	100
16	0.80	250

a) Plot a graph with these readings

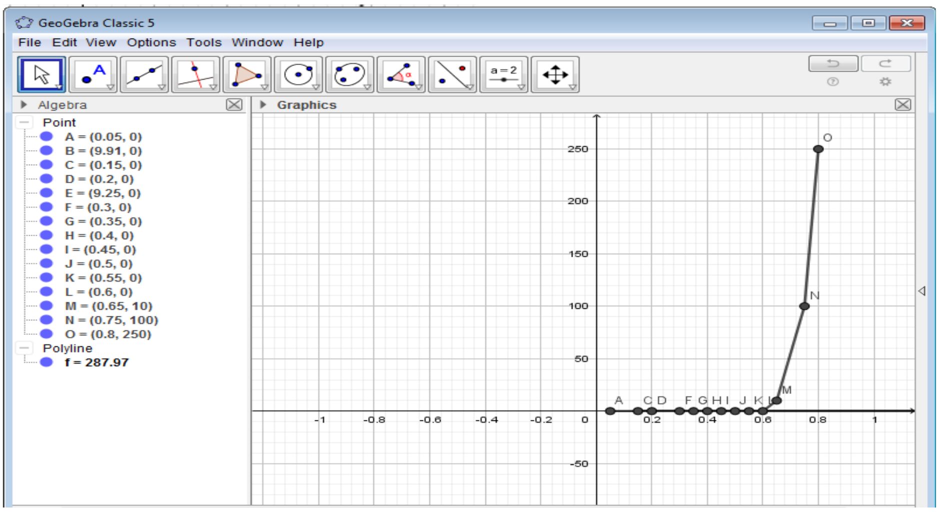
b) Up to s. no 13 the value of current recorded is 0. Explain

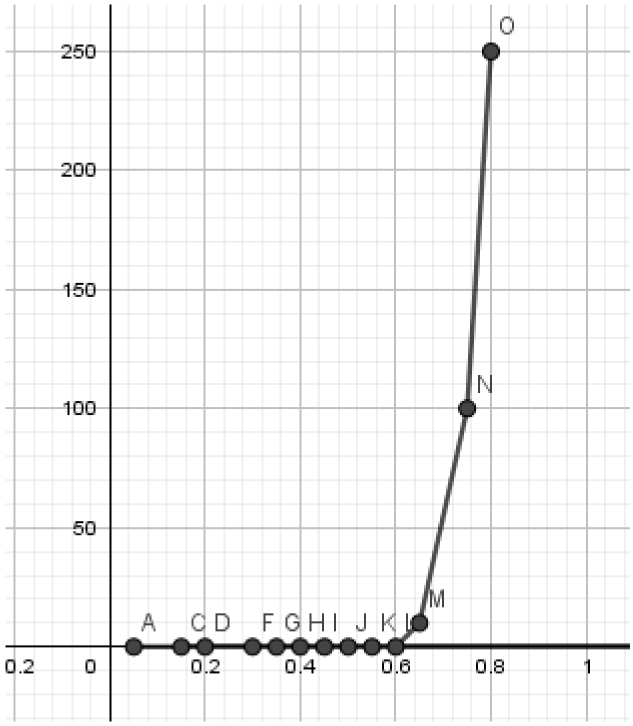
c) Why do we use small voltages for forward bias?

d) Why is the current value small and in mA?

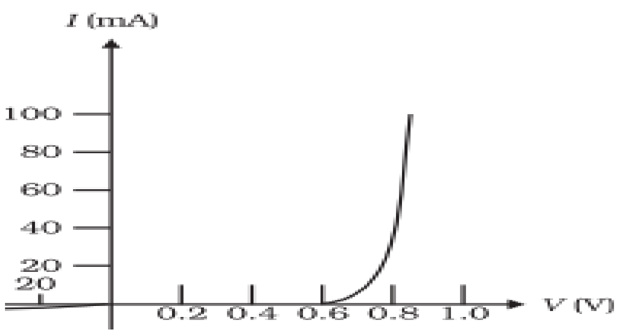
Solution

a) Use Geogebra or plot on a graph sheet





GeoGebra graph Similar to what see in the book



b) The barrier potential does not allow current flow across the junction till the forward bias voltage exceeds the knee voltage.

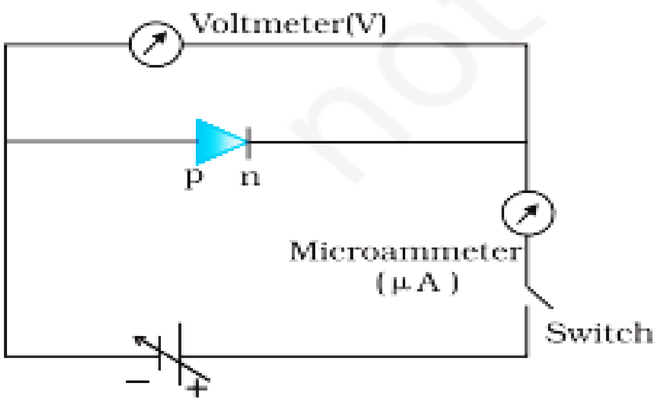
c) To maintain the junction small voltages are appropriate across it, or else we will damage the device.

d) The flow of charge carriers electrons and holes is of the order of mA, the values may change according to doping levels

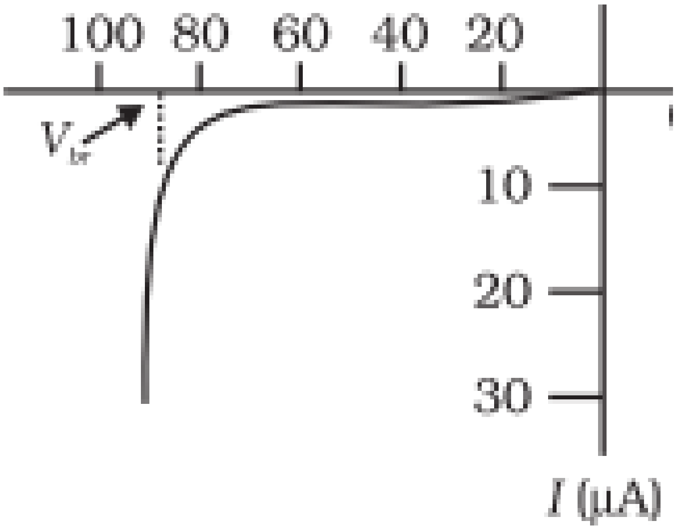
Reverse Bias Characteristics

Reverse characteristics is a quantitative plot between the reverse bias voltage applied across the diode and the reverse current flowing through it.

- Make the circuit as shown in the diagram.
- Now the diode is connected in reverse bias. Increase the reverse bias voltage and note the corresponding reverse current.
- The plot, between reverse current and reverse voltage is shown below



(b)



As can be seen from the graph

- Even for quite a large reverse bias voltage, the reverse current is very small, of the order of a few microamperes.
- At a certain reverse bias voltage, known as the breakdown voltage, the reverse current suddenly starts to increase rapidly.This current is called reverse saturation current.
  If this reverse saturation current increases beyond the rated value of the diode, it might damage it.
- The resistance offered by the diode in reverse bias is quite high.However, for special cases, at very high reverse bias (break down voltage), the current suddenly increases. The general purpose diodes are not used beyond the reverse saturation current region.

- The p-n junction diode primarily allows the flow of current only in one direction (when it is forward biased).
- The forward bias resistance is low as compared to the reverse bias resistance. This property of the p-n junction diode is used for rectification of ac voltages.

Dynamic Resistance of the Junction Diode

The **I-V** characteristics of a p-n junction diode during forward /reverse biasing) is not a straight line. We therefore cannot have a unique (constant) value for the resistance of the diode. We can, however use the basic definition of resistance

$$resistance = \frac{change\ in\ potential\ difference}{corresponding\ change\ in\ current}$$

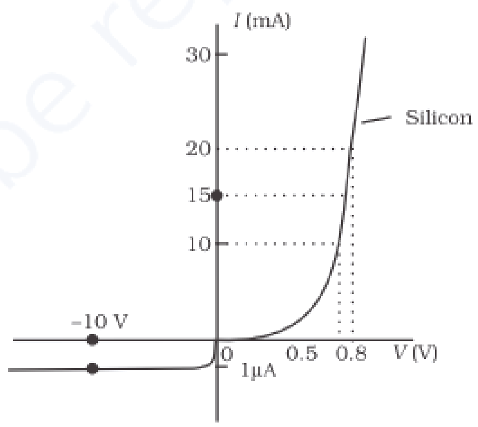
We can use it to define

Dynamic resistance of a junction diode (for a particular value of the applied /current flowing) is defined as **the ratio of small change in the applied potential across the diode to the corresponding small change in the junction current**.

$dynamic\ resistance\ = \frac{\Delta V}{\Delta I}$

Example

The V-I characteristic of a silicon diode is shown in the graph.



Calculate the resistance of the diode (a) at I_D = 15 mA and (b) for V_D = – 10 V

Solution

We think of the diode characteristics to be approximately a straight line between I = 10 mA to I = 20 mA

We can then calculate the resistance using Ohm's law.

a. From the curve, it is seen that for

   I = 20 mA, V = 0.8 V,

   I = 10 mA, V = 0.7 V

   Dynamic resistance

   $= \frac{\Delta V}{\Delta I} = \frac{0.1V}{10mA}$ = **10 Ω**

b. From the curve at

   V = –10 V, I = –1 μA,

   Therefore, **dynamic resistance = 10 V/1μA= 1.0 × 10^7 Ω**

Summary

In this module we have learnt

- Semiconductors are elemental (Si, Ge) as well as compound (GaAs, CdS, etc.).
- Pure semiconductors are called 'intrinsic semiconductors'. The presence of charge carriers (electrons and holes) is an 'intrinsic' property of the material and these are obtained as a result of thermal excitation. The number of electrons (n_e) is equal to the number of holes (n_h) in intrinsic conductors. Holes are essentially electron vacancies with an effective positive charge.
- The number of charge carriers can be changed by 'doping' of a suitable impurity in pure semiconductors. Such semiconductors are known as extrinsic semiconductors. These are of two types (n-type and p-type).
- In n-type semiconductors, ne >> nh while in p-type semiconductors nh >> ne .
- n-type semiconducting Si or Ge is obtained by doping with pentavalent atoms (donors) like As, Sb, P, etc., while p-type Si or Ge can be obtained by doping with trivalent atoms (acceptors) like B, Al, In etc.
- $n_e \times n_h =$ in all cases.
- n-type and p-type semiconductors possess an overall charge neutrality.
- There are two distinct bands of energies (called valence band and conduction band) in which the electrons in a material lie. Valence band energies are lower as compared to conduction band energies. All energy levels in the valence band are filled while energy levels in the conduction band may be fully empty or partially filled. The electrons in the conduction band are free to move in a solid and are responsible for the conductivity. The extent of conductivity depends upon the energy gap (E_g) between the top of the valence band (E_V) and the bottom of the conduction band E_C . The electrons from the valence band can be excited by heat, light or electrical energy to the conduction band and they can then produce a change in the current flowing in a semiconductor.
- For insulators Eg > 3 eV, for semiconductors Eg is 0.2 eV to 3 eV, while for metals Eg ≈ 0. 12.
- p-n junction is the 'key' to all semiconductor devices. When such a junction is made, a 'depletion layer' is formed consisting of immobile ion-cores devoid of their electrons or holes. This is responsible for a junction potential barrier.
- By changing the external applied voltage, the effective value of the voltage across the junction barrier can be changed.

- In forward bias (n-side is connected to the negative terminal of the battery and p-side is connected to the positive), the barrier is decreased while the barrier increases in reverse bias. Hence, forward bias current is more (mA) while it is very small (μA) in a p-n junction diode.