

Module 1 : Junction Diode

This module is designed to help you to:

- distinguish between conductor, insulator and semiconductor on the basis of energy gap between the valence and conduction bands and hence relate the conductivity of the material with the energy gap;
- discuss the advantages of semiconductors over conductors and insulators and their use in the fabrication of materials with desired level of conduction;
- distinguish between intrinsic and extrinsic semiconductors;
- explain the characteristics of p and n-type semiconductors;
- discuss the fabrication of the p-n junction diode;
- interpret the V - I characteristics in forward and reverse bias of the p-n junction diode;
- explain the working of a Zener diode.

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14.1.1 Introduction

Semiconductors are used in almost all modern gadgets like pocket calculators, cell-phones, TV sets, smart cars, portable radios, computer chips, telephones, robots, solar cells, medical equipment, space stations, and so on. Thus, it is of significant importance to study the basic physics and applications of semiconductors.

We shall begin by giving a brief about the concepts of energy bands, primarily the meanings of valence and conduction bands. Based on that we shall provide the points of differences between conductors, insulators, and semiconductors.

Semiconductors are of two types - intrinsic and extrinsic. Again among the latter, there are two types: n-type and p-type. We shall understand the mechanism of conduction in these semiconductors where we will come across terms such as donor and acceptor and most importantly the hole.

A p-n junction is the most fundamental application of extrinsic semiconductors. It behaves like a valve, which allows movement in only one direction. We shall study the I - V characteristics of this device and subsequently its use as a rectifier. Finally, we shall also study about a zener diode.

14.1.2 Metals, insulators and semiconductors

Let us first familiarise ourselves with the varying conduction properties of different types of materials. We shall do so with the help of the Table 14.1.1 given below.

Table 14.1.1 Comparison of some important properties of conductors, semiconductors and insulators.

S.No.	Characteristics	Conductors	Semiconductor	Insulator
1.	Charge carriers	Electrons	Electrons and holes	No free charge carriers
2.	Resistivity	Very low ($10^{-2} - 10^{-8} \Omega\text{m}$)	High at low temperatures, Moderate to low at high temperatures, of the order of $10^6 \Omega\text{m}$	Very high ($10^{11} - 10^{19} \Omega\text{m}$)

3.	Temperature dependence of resistivity	Increases with increase in temperature	Decreases with increase in temperature	an insulator at very low temperature may become semiconductor or conductor at high temperature e.g. pure silicon or germanium
4.	Effect of doping (impurity addition)	Minimal; Resistivity increases	Resistivity decreases significantly with use of suitable dopants	Conductivity may change depending on the nature of impurity
5.	Effect of irradiation of light	Characteristics remain largely unaffected	Changes significantly	Remains unaffected

We have seen the distinctions between the properties of conductors, insulators and semiconductors. We shall invoke the concept of energy bands to take a deeper look at these distinctions.

14.1.3 Energy bands

We know about electron energy levels in an isolated atom. But in a solid the atoms do not remain isolated. Rather they come extremely close to each other. When two atoms A and B come near each other, then, the electron energy levels corresponding to atom A become available to atom B and vice versa. In other words, the energy levels will tend to overlap. But, no two electrons can have all the quantum numbers same, which describes an energy level. So, the levels can not just coincide but tend to spread out. And in the case of multiple atoms, the levels smear out in the form of continuous energy levels and we get what is called an energy band.

The energy band which includes the energy levels of valence electrons is called a valence band and the band having higher energy than the valence electrons is called the conduction band.

We shall take a look at the distinction between conductors, insulators and semiconductors on the basis of the above concept of energy bands. In conductors, there is no gap between the valence and conduction bands or they overlap each other. Therefore, even room temperature energy is sufficient to excite *valence electrons* to the conduction band and make them available for conduction of electricity.

The behaviour of insulators can be explained on the basis of the large energy gap between their valence and conduction bands. Since the band gap is quite large, it may not be possible, with ordinary sources, to provide high voltages that can provide sufficient energy to valence electrons that may excite them into the conduction band. Therefore, there will be very few, or no, mobile charge carriers to constitute an electric current.

In semiconductors, there is a small energy band gap between the valence band and the conduction bands. This gap is more than that of conductors but much less than that of insulators. Hence it is possible to have an electric current through them with relatively small voltages.

At room temperature, some electrons in the valence band may have energy to get excited to the conduction band. Thus materials that are insulators at low temperatures can behave as semiconductors at room temperature.

The Valence Bands (VB), the Conduction Bands (CB), and Energy Gap (E_g) for conductors, insulators and semiconductors have been shown schematically in Fig 14.1.1.

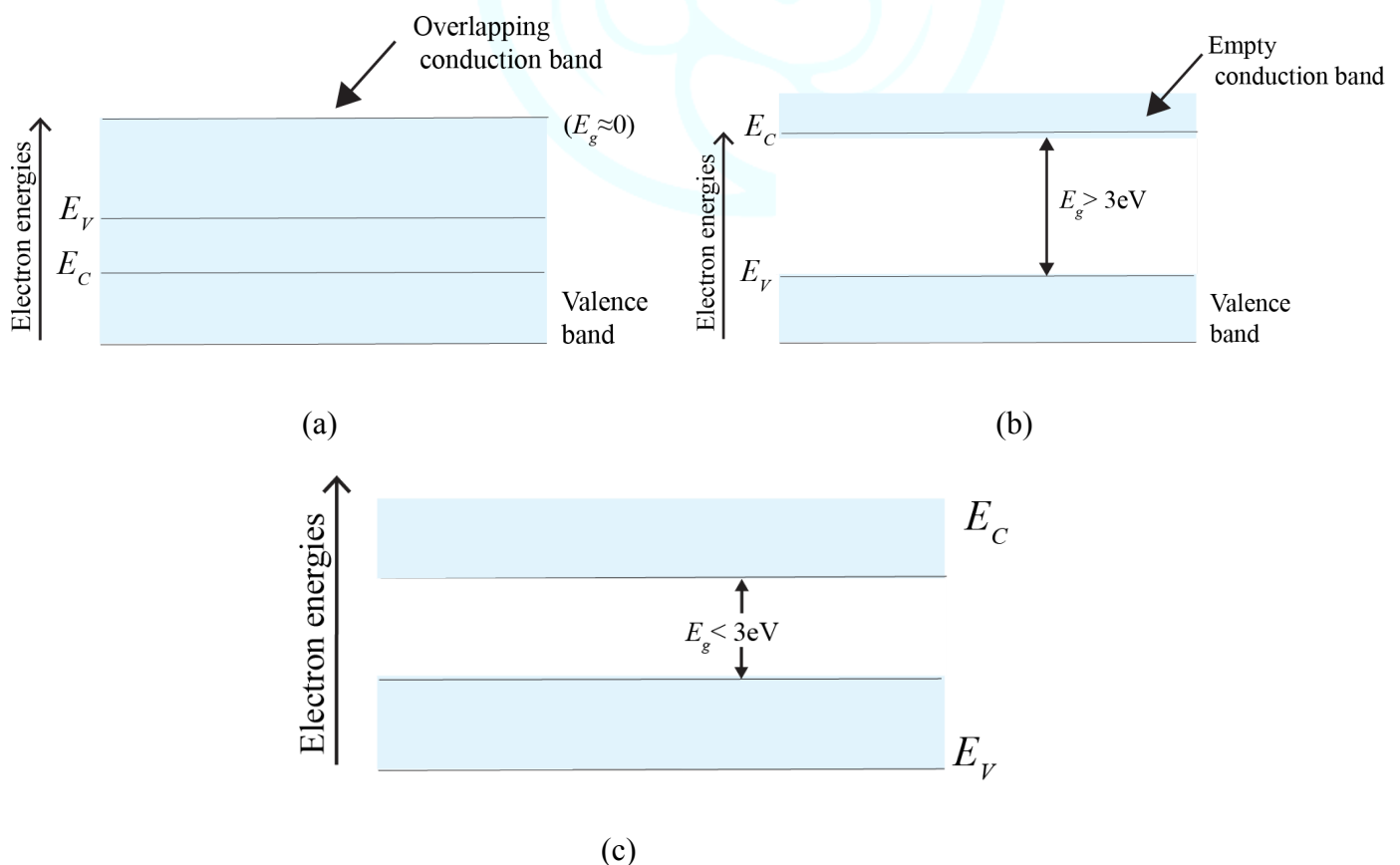


Fig 14.1.1 Conduction band, valence band and energy gap in (a) Conductors, (b) Insulators and (c) Semiconductors

We can also manipulate the type of mobile charges in a semiconductor, by doping (adding) it with suitable impurities. The description of the resistivity of a semiconductor is therefore dependent upon conditions like whether it is pure or doped, and, if doped, the type of doping. Let us look into these aspects in the following discussion.

A question that may arise here is: “when we have so many easily available and affordable conductors, with very low resistivity, what is the need to use various seemingly complex methods, to decrease the resistivity of semiconductors”?

Advantages of semiconductors over conductors or insulators:

1. A conductor conducts electricity while an insulator does not conduct. This basic property of the conductor, or insulator, cannot be changed by merely making small changes in the potential difference across it. In the case of extrinsic semiconductors, it is possible to control the flow of charge by adding a suitable amount of impurity.
2. The resistance of a conductor or an insulator remains fixed, that of the semiconductor can be made desirable with the right amount of impurity.
3. It is possible to make a memory device with a semiconductor using suitable circuitry.
4. One can use semiconductors to operationalize Boolean Algebra which happens to be the chief guiding principle behind digital devices.

The very significant change in resistivity of semiconductors, through doping makes them the most sought-after materials in the electronics industry today. This characteristic enables semiconductors to be used as ‘tailor-made materials’ for different applications.

Semiconductor based devices offer the following advantages:

- Miniaturization - small in size, light in weight
- Low power consumption
- Higher reliability and longer service life
- More robust; can stand up to more vibrations, impacts and other physical factors
- Cost effective

In order to sensitize you about the wonders that can be achieved in the world of devices using semiconductors, a block diagram (Fig 14.1.2) is given below.

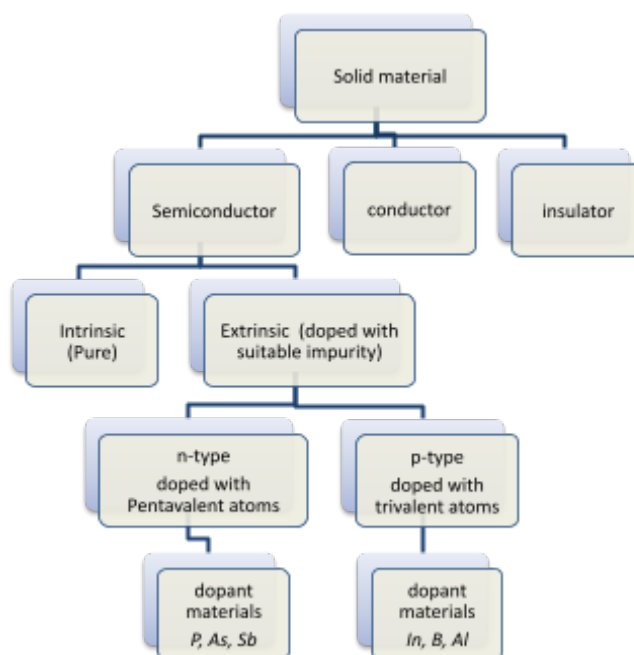


Fig. 14.1.2 A Block diagram as a precursor for devices using semiconductors

We have introduced a few new terms in Fig 14.1.2. We shall now explore them in the process of learning more about semiconductors, which can be classified as under:

1. Pure/*intrinsic* semiconductors
2. Impure/*extrinsic* semiconductors

14.1.4 Intrinsic semiconductors

Intrinsic semiconductors are generally tetravalent (Group 4) pure elements like Si and Ge or can be binary compounds particularly of Group 3 and 5 such as Gallium Arsenide (GaAs), Group 2 and 6 such as Zinc Sulphide (ZnS) and between different Group 4 elements such as Silicon Carbide (SiC) so as to have average valency of 4 and have no mobile charge carriers at the absolute zero of temperature. Hence, they behave as perfect insulators at 0 K. However, by increasing the temperature, some of the *valence electrons* can become *conduction electrons*. Simultaneously, there is a vacancy for electrons in the parent atoms from which they are ejected. This vacancy acts as if it is a positive charge, it has been given the name hole.

Let us try to understand this mechanism with the help of an analogy. A garage has five cars arranged in a straight line as shown in Fig 14.1.3(a). A car inside the garage is like a bound electron. When it moves out,

then each of the other four cars moves one step ahead and a vacancy is created at the other end as shown in Fig 14.1.3(b). As a matter of fact, the vacancy is created first at the right extreme and with the movement of the cars inside the garage, the vacancy moves to the other end. This is further clarified with the help of the examples of two cars moving out and correspondingly two vacancies getting created as shown in Fig. 14.1.3(c). These vacancies move in a direction opposite to that of the electrons and are hence deemed to have positive charge. These vacancies are analogous to the holes.

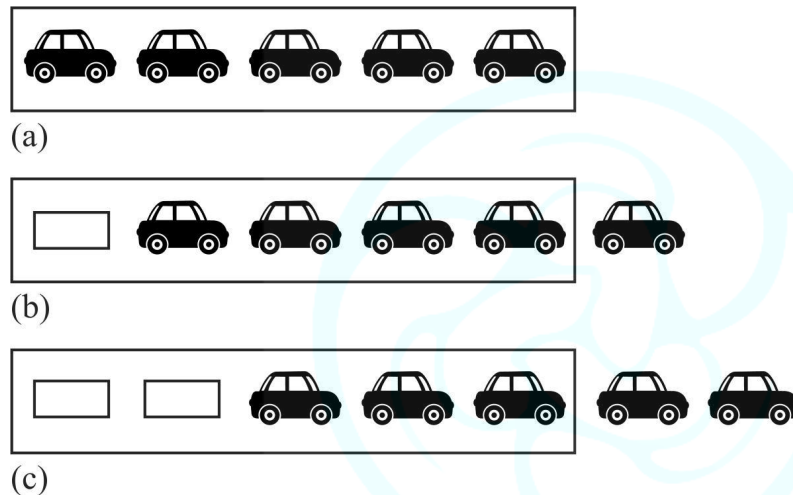


Fig 14.1.3 The analogy of movement of cars inside and outside a garage with the creation of electron-hole pairs and their movement as charge carriers

Thus, we have seen how it gives rise to a free electron in the conduction band and a free hole in the valence band. This process is known as ‘Generation’. The reverse may also happen, that is combination of a free electron and a free hole to become a bound electron. This process is known as ‘Recombination’. The process of conduction in a semiconductor is an interplay between Generation and Recombination.

Both free electrons and holes contribute to electric current. When temperature increases, an increasing number of thermal electron-hole pairs behave as charge carriers and the resistivity of intrinsic semiconductors decreases. Except for the temperature of 0 K, intrinsic semiconductors always show some small conductivity due to the production of electron and hole pairs by thermal energy. Holes, being essentially electron vacancies each of them has an effective positive charge equal to $+e$. If n_e = number density of free electrons and n_h = number density of holes, we have $n_e = n_h$ in a pure (intrinsic) semiconductor.

This method of increasing the temperature to generate additional mobile or free charge carriers has limitations. A question may be asked: “Does a neutral intrinsic semiconductor become charged due to the production of thermal electron-hole pairs in it”?

Surely not. There being no external addition of any charge, the thermal electron-hole pairs still maintain their neutrality.

Now we shall present the mechanism of conduction in an intrinsic semiconductor using the schematic diagrams as shown in Fig 14.1.4.

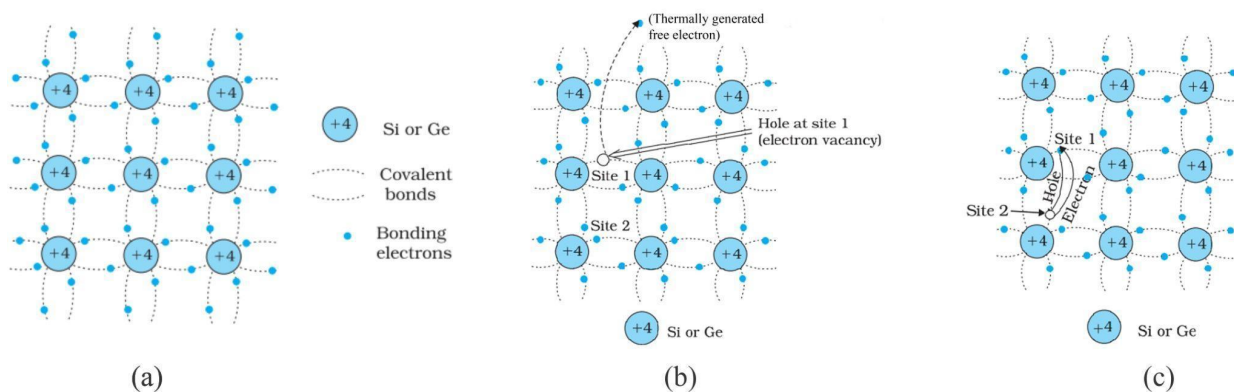


Fig 14.1.4 (a) Two-dimensional representation of Silicon (Si) and Germanium (Ge) structure
 (b) Generation of hole at an electron vacancy
 (c) Possible thermal motion of a hole

Fig 14.1.4(a) is the two dimensional representation of Si and Ge structures which depicts the covalent bonds and the sharing of electrons. Fig 14.1.4(b) shows the generation of conduction electrons due to thermal excitation and that of the corresponding hole at site 1. Fig 14.1.4(c) shows the thermal motion of a hole. The electron from site 2 goes to the earlier hole site 1, thereby leaving a hole at its site which is indicative of the motion of the hole from site 1 to site 2.

Now that we have understood the mechanism of conduction in an intrinsic semiconductor, let us go over to study extrinsic semiconductors.

14.1.5 Extrinsic semiconductors

Extrinsic semiconductors are semiconductor samples that have been doped with suitable impurities in required proportion. Instead of using the heating method, the conductivity of intrinsic semiconductors can be increased by doping them with a suitable impurity. Depending upon the type of doping, either the free electron density or the hole density can be increased. Hence $n_e \neq n_h$ in an extrinsic semiconductor.

It may be noted that the 'doping effect' will be over and above the generation of thermal electron-hole pairs by thermal energy.

First we shall study n-type semiconductors.

14.1.5.1 n-type semiconductor

It is produced by using pentavalent doping (P, As, Sb, etc.) impurity to 'dope' a pure Ge or Si type semiconductor. In these types of semiconductors, the fifth electron of the impurity atom does not form any bond with the atoms of Ge or Si. Hence the fifth electron is available for electrical conduction. Hence electrons are the majority of charge carriers in such a semiconductor. The mechanism is explained through the schematic diagram Fig 14.1.5.

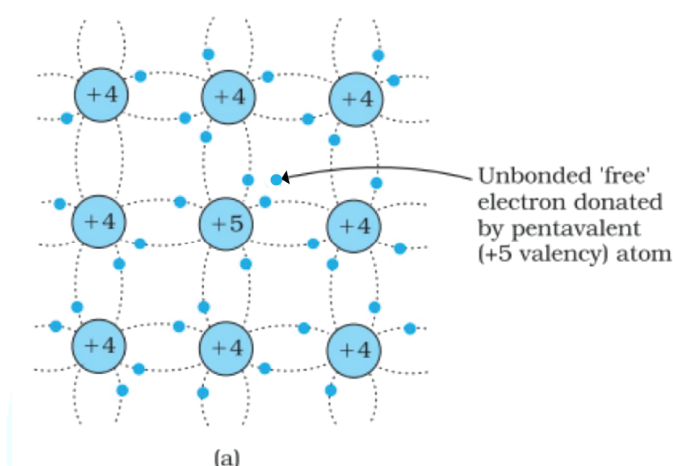


Fig 14.1.5 Pentavalent donor atom (P, As, Sb, etc.) doped in a tetravalent Si or Ge site giving rise to n-type semiconductor

The impurity pentavalent atom effectively donates an electron to the original site, and so it is called a donor and the energy level occupied by it is called the donor level.

14.1.5.2 Donor level

An isolated electron is completely free from any electrostatic attraction; hence it will easily produce current by flowing towards higher potential. Its energy level will lie in the conduction band. However, what we term as *free electrons*, in a n-type semiconductor, is neither isolated nor completely free. We may just say that, compared to bound electrons, it is relatively free and easily available for conduction. Further, the *free electron* in a n-type semiconductor experiences some force of attraction from the positive nuclei near the electron. Therefore, its energy level is 'lower' than that of an isolated electron and falls just below the conduction band. This is called the 'donor level'. To enable it to contribute to the current flow, one has to

supply (small) energy to it. An equivalent statement would be; ‘to raise it to a conduction band, one has to supply it with a small amount of energy.’

For example, the energy required is of the order of 0.01 eV and 0.05 eV for Ge and Si respectively, which is quite a contrast from the respective figures of the energy gaps in cases of Ge and Si which are 0.72 eV and 1.1 eV respectively. A schematic diagram of the donor level is given in Fig 14.1.6.

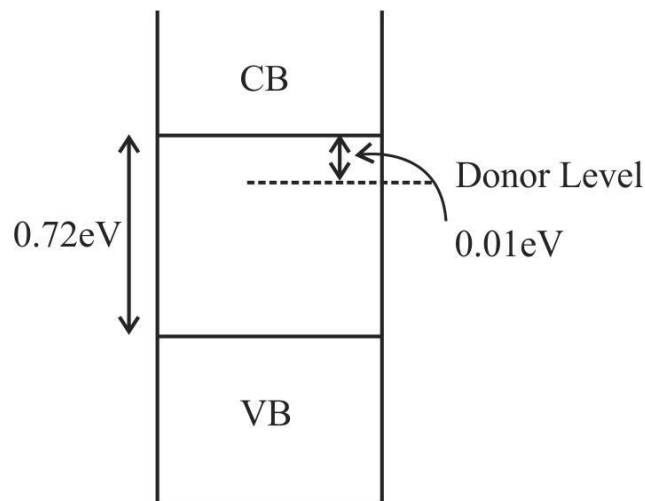


Fig 14.1.6 Donor level in an extrinsic semiconductor (from a Ge atom) lying just below the conduction band

Now let us study p-type semiconductors.

14.1.5.3 p-type semiconductor

It is produced by using a trivalent (In, B, Al, etc.) impurity atoms to ‘dope’ a pure semiconductor. In these types of semiconductors, the vacancy of the fourth electron in the impurity atom does not form any bond with the atoms of the parent material. The vacancy acts as if it were a positive charge. A valence electron in its neighborhood, may jump into this vacancy (Fig 14.1.7) and result in a shift in the position of the vacancy. In this way, the vacancy (hole) moves from one position to the other. Thus a ‘hole’ current flows in the material. It is equivalent to the flow of positive charges.

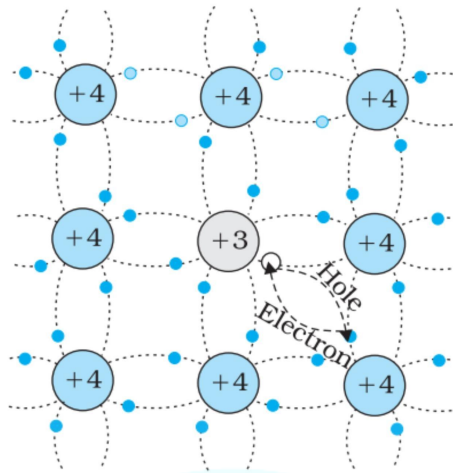


Fig 14.1.7 Trivalent acceptor atom (B, In, Al, etc) doped in a tetravalent Si or Ge site giving rise to p-type semiconductor

The impurity trivalent atom effectively accepts an electron from the original site, and so it is called an acceptor and the energy level occupied by it is called the acceptor level.

14.1.5.4 Acceptor level

We have already studied the mechanism of the formation of donor level in an n-type semiconductor in sub-section 14.1.5.2. Following the same logic, it can be said that the energy of the acceptor level is 'higher' than that of energy of the valence band. With a very small supply of energy, an electron from the valence band can jump to the acceptor level and ionise the acceptor negatively. At room temperature most of the acceptor atoms get ionised leaving holes in the valence band available for conduction. An equivalent statement would be; 'to set a free hole in motion in the valence band, one has to supply a small amount of energy.' A schematic diagram of the acceptor level is given in Fig 14.1.8.

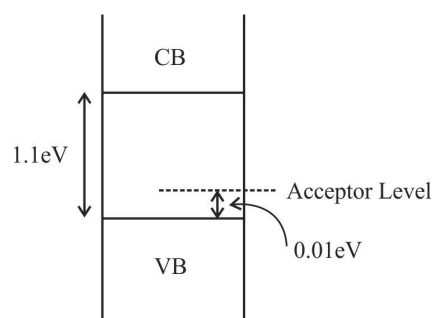


Fig 14.1.8 Acceptor level in an extrinsic semiconductor (from a Ge atom) lying just above the valence band.

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

$$n_e n_h = n_i^2 \text{ where}$$

n_e and n_h are electron and hole concentration and n_i is the intrinsic carrier concentration.

At this stage it is worthwhile to talk a little critically about the role of a hole as a charge carrier. Is it equivalent to a positive charge?

14.1.5.5 Distinction between a positive charge and hole

The statement that a hole is ‘equivalent to a positive charge’ should not be taken at just its face value. We need to appreciate that:

- A positive charge can be free but a hole is bound.
- A positive charge can move by itself. A hole does not move by itself. If another valence electron jumps into a vacancy, the hole appears to have moved to a new position. The motion of the holes is, therefore, caused by the motion of valence electrons.
- The energy level of a completely free positive charge lies in the conduction band, and that of the hole lies just above the valence band.

The production of holes, in an intrinsic semiconductor, produces an additional energy level, just above the valence level, but close to it. We can produce a *hole current* by supplying small energy to valence electrons. The valence electrons jump into holes in the *acceptor level*, to produce an electric current.

Are n-type or p-type, extrinsic semiconductors, neutral after their doping?

Both n-type and p-type extrinsic semiconductors are also electrically neutral because pure semiconductors are neutral and the materials, with which they are doped, are also electrically neutral.

We shall now see what happens when a p-type semiconductor is combined with an n-type semiconductor.

14.1.6 P-N junction diode

A pure silicon crystal can be doped such that one part is doped by pentavalent impurity and the other part by trivalent impurity. Thus it develops two regions one p-type and n-type. This leads to the formation of a p-n junction. A p-n junction is schematically represented as shown in fig.14.1.9.

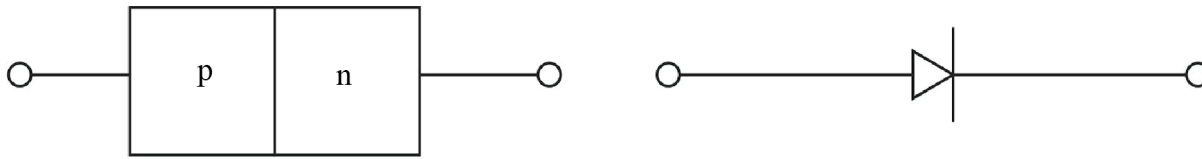


Fig 14.1.9 Schematic representation of p-n junction

Now that we have got the desired idea about the creation of a p-n junction, we may go ahead to understand the mechanism of conduction through this device, and the first step towards that is to know about the depletion region.

14.1.6.1 Depletion region

It is well known that in an n-type semiconductor, the concentration of electrons 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. A concentration gradient is thus created across p- and n- sides of a p-n junction.

The concentration gradient results in the diffusion of holes from p- side to n- side. On the other hand, electrons diffuse from n- side to p- side. This motion of charge carriers gives rise to a diffusion current across the junction. When an electron diffuses from n→p, it leaves behind an ionised donor (immobile positive charge) which is bonded to the surrounding atoms. As the electrons continue to diffuse from n→p, a layer of positive charge is developed on the n-side of the junction. Similarly, when a hole diffuses from p→n, it leaves behind an ionised acceptor (immobile negative charge) which is bonded to the surrounding atoms. The diffusion of holes from p→n thus leads to the formation of a layer of negative charge on the n-side of the junction. The movement of the electrons and holes on account of diffusion across the junction depletes the region of its free charges. This space-charge region on either side of the junction together is thus known as the depletion region. It has been shown in Fig 14.1.10.

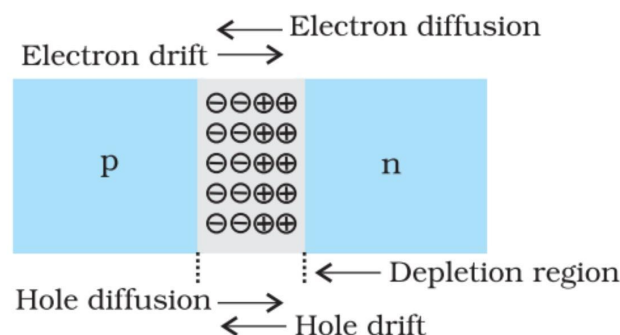


Fig 14.1.10 Depletion region in a p-n junction

Before proceeding further with the understanding of the operations of a p-n junction, let us try to have a feel about a p-n junction — What does it look like? How does it differ from an ordinary resistor?; and so on.

14.1.6.2 Having the feel of a p-n junction

It has been observed that our students often do not get to see easily available affordable components like diodes, transistors, gates, etc. So, it is advisable to show these components to them while discussing the relevant theory in the classroom. Let them observe different types of diodes, like the p-n junction diode, Zener diode, light emitting diode and photodiode. It is easy to identify p- and n-sides of the diodes by mere observation. But here we shall also tell about the application of electrical methods for identifying p and n sides.

Students should be given an activity to measure the resistance of a carbon resistor and a p-n junction diode with the help of a multimeter. They should observe the difference on changing the leads of the multimeter connected to the two ends of the p-n junction diode.

Activity 14.1.1

- To show that a resistor is a bi-directional device.
- To identify and distinguish between a resistor and a diode using a multimeter (ohmmeter).

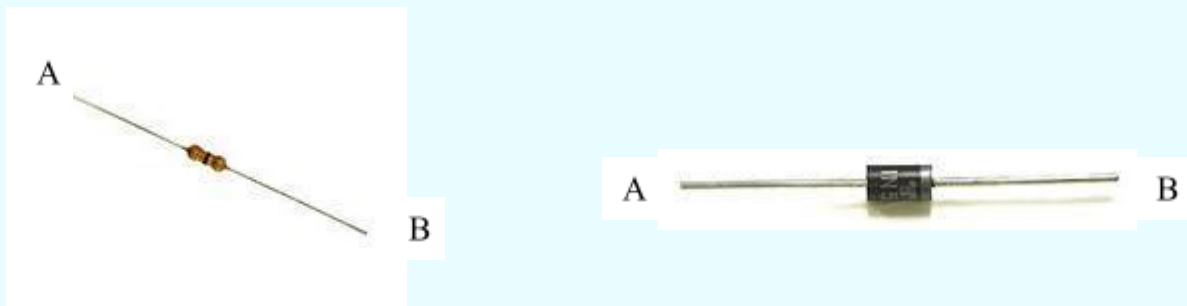


Fig 14.1.11



Fig 14.1.12

Sr. No.	Item	Resistance (Ω) When red lead of the ohmmeter is connected to A and black lead is connected to B	Resistance(Ω) When black lead of the ohmmeter is connected to A and red lead is connected to B	Comment	Inference
1	Resistor				
2	Diode				

Measure the resistance between A and B of a resistor using an ohmmeter. Interchange the terminals, i.e. measure the resistance between B and A. It will be observed that in both the cases, the ohmmeter will read the same.

Repeat the same procedure with a diode. It will be observed that the ohmmeter will not show the same readings. In one case the resistance would be high and, in another case, a low value of resistance will be observed.

After doing this activity, students will find that, in the case of a resistor, there is no effect of changing the leads, as in the case of a p-n junction diode they will observe that in one case it shows small resistance whereas in other cases it shows a high resistance.

Note: The students may be told that the red lead of the multimeter is connected internally with the negative terminal of the battery and black (common) is connected with the positive terminal of the battery.

The above activity is an indication about a p-n junction allowing the flow of current only when it is connected in a particular way and not in its reverse mode. In other words, it acts like a diode valve, so it is often referred to as a diode. We shall have a deeper understanding when we study the instances of forward and reverse bias in the subsequent sections.

Activity 14.1.2

Here we introduce the concept of p-n junction as a switch. If we connect the device with p- side connected to the higher potential terminal/point and n- side connected to the lower potential terminal/point then it offers very low resistance (ideally = zero ohm). Current can flow easily through it which acts here as a

closed switch. When we reverse the connections, it will offer very high resistance (ideally infinite) and current cannot flow easily through it. So the device works like an open switch.

Through the above activities, you have got a feel for the functioning of a p-n junction. Let us now consolidate our understanding about the same.

14.1.6.3 p-n Junction in forward and reverse bias

Forward Bias: When p- side of the junction is connected to the positive, or higher potential and n- side to the negative or lower potential, such that the applied potential difference between p and n sides of the junction is more than 0.7 V (for Silicon) or 0.3 V (for Germanium) then the p-n junction diode is said to be ‘forward biased’.

Reverse bias: When the p- side of the junction is connected to the negative potential terminal/point and n side at positive potential, the diode is said to be reverse biased.

The connections and the current-voltage characteristics in forward and reverse bias are shown in Fig 14.1.13 and Fig 14.1.14 respectively.

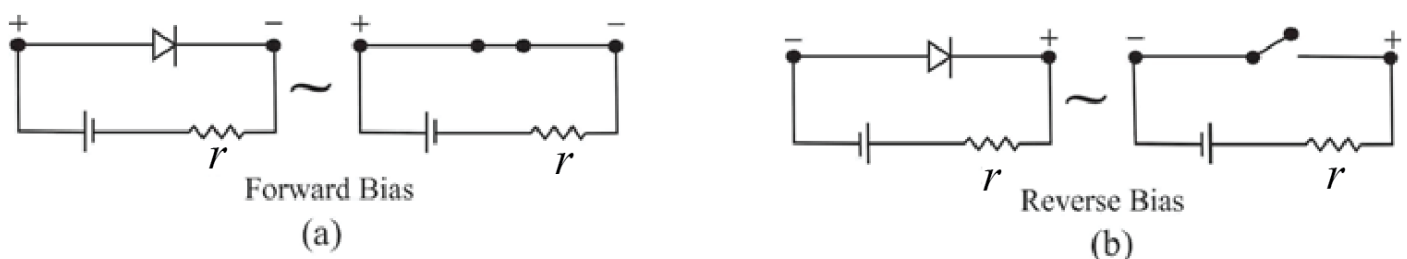


Fig.14.1.13 *p-n junction in forward and reverse bias*

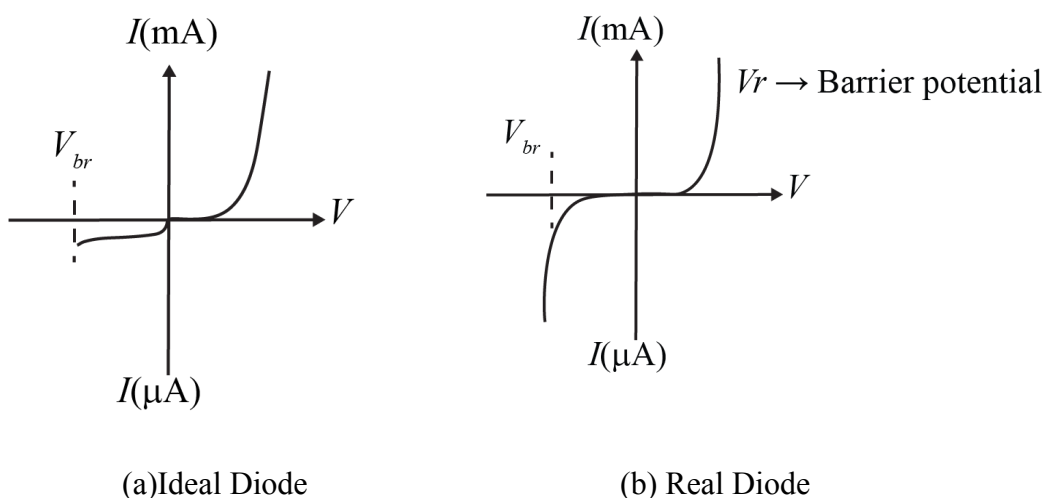


Fig 14.1.14 *Current-voltage characteristics in forward and reverse bias of (a)an ideal diode (b)a real diode*

Ideal diode: The word “ideal” with a diode is used to explain the features of a diode. No diode is an ideal one. To simplify the analysis of diode circuits, we often use this concept. According to assumptions, an ideal diode (i) conducts with zero junction resistance during forward bias and (ii) offers infinite resistance during reverse bias.

Therefore it behaves like a switch, which is ‘closed’ when forward biased, and ‘open’ during reverse bias.

Real diode: Real diodes do not conduct with zero junction resistance during forward bias. However, its resistance decreases as the forward bias increases and after the forward bias crosses the barrier potential value, the diode resistance approaches a constant value. *We have read that the depletion region is devoid of any mobile charge carrier . In other words, it creates a barrier to the flow of charge carriers in no-bias conditions. The potential energy that quantifies this barrier is called the barrier potential. Forward bias helps in overcoming the barrier, whereas during reverse bias the barrier height gets increased. During reverse bias, the diode does not offer infinite resistance, actually a leakage current due to minority charge carriers, and surface leakage current always flows (whether the diode is forward or reverse biased) through the junction. Since a current is flowing, it means resistance has some measurable value and is not infinite. With this background, we can understand the most crucial application of rectification by a p-n junction diode.*

14.1.6.4 p-n junction as a rectifier

The action of rectification means conversion of AC to DC. However, the first stage is to get a unidirectional output from an AC input. It can happen in two ways - (i) Only half part of the full input cycle remains after rectification, (ii) Both the half parts appear after rectification giving a non-zero unidirectional output throughout the cycle. These are shown in the Fig. 14.1.15(a), (b), (c).

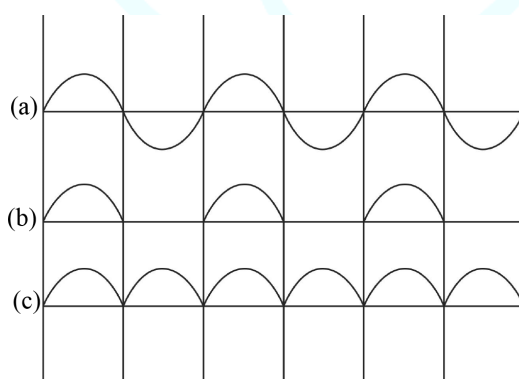


Fig 14.1.15 (a) AC input

(b) Half wave rectified output of the AC input

(c) Full wave rectified output of the AC input

The action of rectification can be explained as under:

Refer to Fig 14.1.16 (a) and (b).

Forward biasing of a real diode, can be imagined as a combination of an ideal diode in series with a battery of low emf, (connected in reverse biasing condition), and a variable resistance.

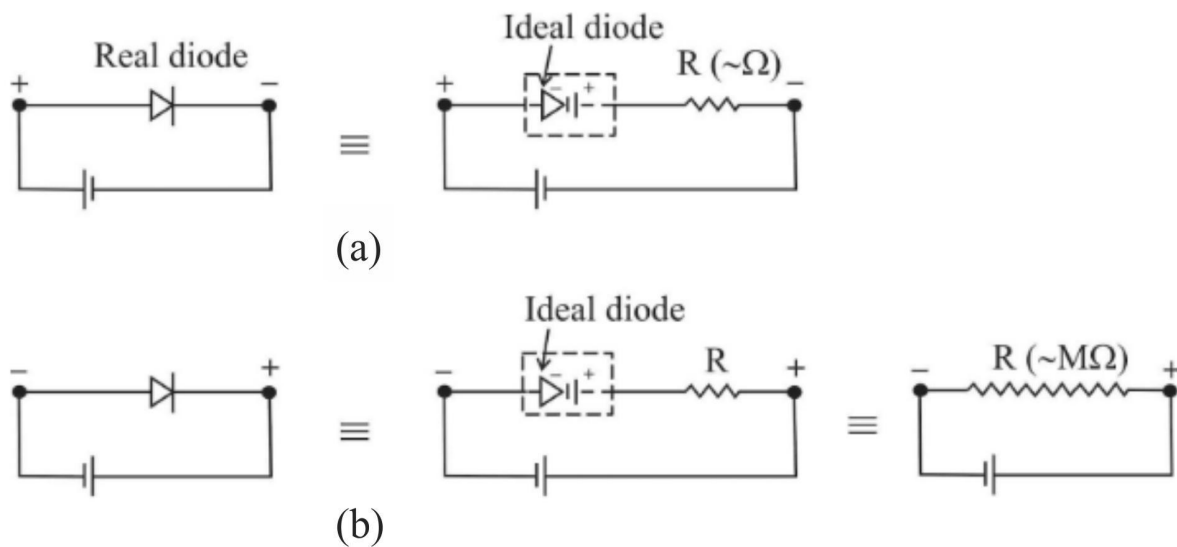


Fig: 14.1.16 (a) Real diode in forward bias

(b) Real diode in reverse bias

For reverse biasing, a real diode can be imagined as a resistor of a very high value.

In case of forward biasing the opposing battery has very small emf (0.2 V for Ge and 0.7 V for Si) and resistance R is also very small. Therefore, the practical diode can also be assumed to be conducting without offering much resistance, during forward bias. During reverse bias, R is very high, The diode can be assumed to be non-conducting (practically a very small current flows).

We have seen in the I - V characteristics of the p-n junction in the reverse bias, that there is a huge surge in the value of the current during the reverse bias at a certain value of the negative voltage, and this is referred to as the breakdown voltage (Fig 14.1.14).

Thus the diode can act as a switch, which is 'open' when reverse biased, and 'closed' when forward biased, and so it acts as a rectifier.



Q.14.1.1 State the meaning of the term, 'doping of an intrinsic semiconductor'. How does it affect the conductivity of a semiconductor?

Q.14.1.2 Why are elemental dopants for silicon or germanium usually chosen from group III or group V?

Q.14.1.3 What are the different applications of semiconductors in our daily life?

Q.14.1.4 How can you distinguish between a resistor and a diode with the help of a multimeter?

Q.14.1.5 What is an ideal diode? Draw the output waveform across the load resistor R , if the input waveform is as shown in Figure 14.1.17.

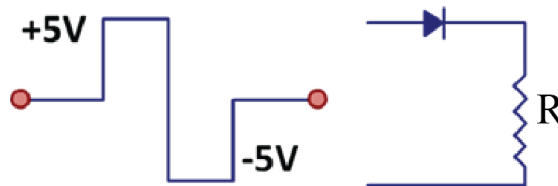


Fig: 14.1.17

Q.14.1.6 Observe the following diagrams and indicate which of the diodes are forward biased and which are reversed biased?

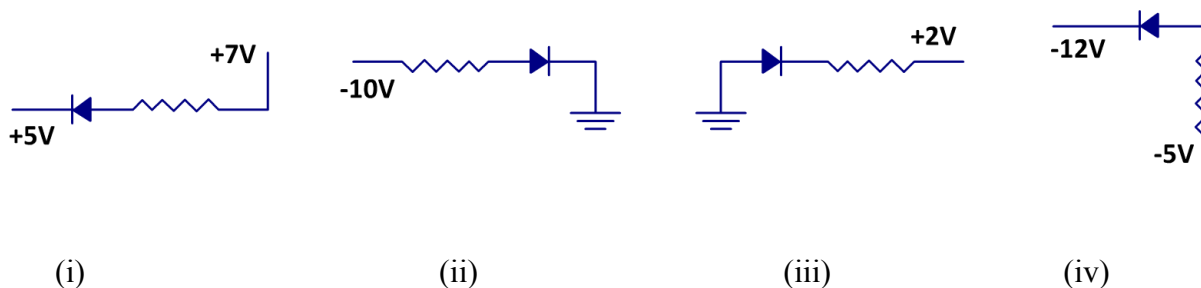


Fig: 14.1.18

Q.14.1.7 In a n-type semiconductor, the number of free electrons is greater than the number of holes. Does it have a net negative charge? Justify your answer.

Q.14.1.8 Determine the currents through the resistance R of the circuits (i) and (ii), when similar ideal diodes D_1 and D_2 are connected as shown in Fig.14.1.19

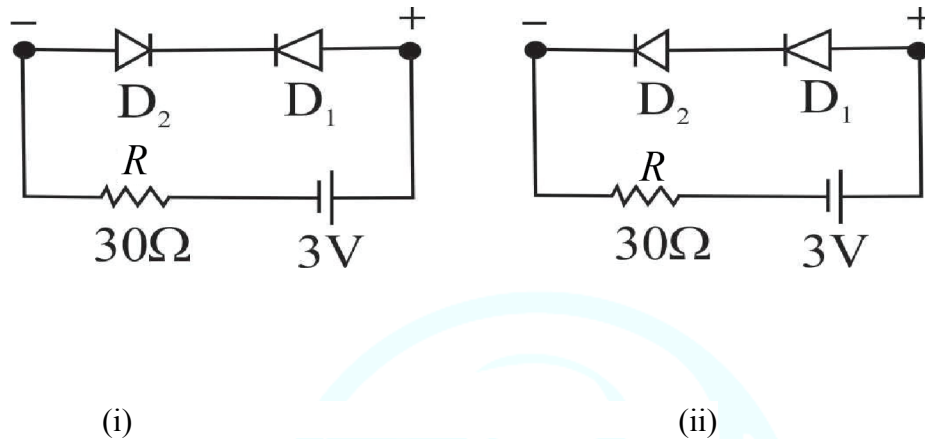


Fig: 14.1.19

Q.14.1.9 Choose the correct option.

The output of the given circuit of Fig.14.1.20

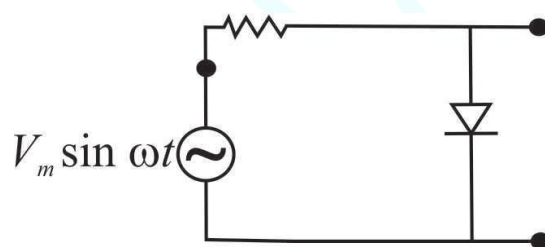


Fig: 14.1.20

- (a) would be zero at all times.
- (b) would be like that of a half-wave rectifier with only positive cycles in output.
- (c) would be like that of a half-wave rectifier with only negative cycles in output.
- (d) would be like that of a full wave rectifier.



Answers

A.14.1.1 When an impurity in the form of trivalent or pentavalent atoms is added to an intrinsic semiconductor then it is called doping of an intrinsic semiconductor. Doping increases the conductivity of a semiconductor.

A.14.1.2 Silicon and Germanium are tetravalent atoms that form covalent bonds with each other sharing 4 electrons with 4 neighbouring atoms. They are doped with group III (trivalent) or group V (pentavalent) atoms to provide excess holes or electrons respectively for increasing conductivity.

A.14.1.3 Semiconductors are used in almost all modern gadgets like pocket calculators, cell phones, TV sets, smart cars, portable radios, computer chips, telephones, robots, solar cells, medical equipment, space stations and so on.

A.14.1.4 A resistor will show the same value of resistance when measured from a multimeter connecting either terminal of the multimeter to either side of the resistor. Thus it is a bi-directional device i.e. they allow flow of current in both directions and their terminals do not have any polarity. In the case of diodes they show very little resistance when measured from a multimeter with a particular polarity of its terminals. If the polarity of the terminals of the multimeter is reversed then the diode will show very high resistance (ideally infinite). Thus diodes are unidirectional devices i.e. they allow the flow of current only in one direction.

A.14.1.5 An ideal diode conducts with zero junction resistance during forward bias and offers infinite resistance during reverse bias (Fig.14.1.21).

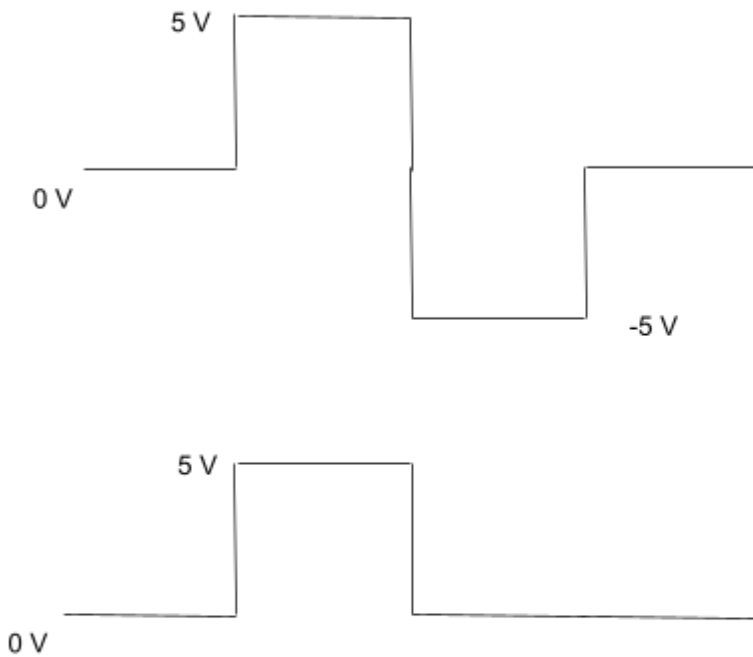


Fig.14.1.21(i) *Input waveform* **(ii)** *Output waveform*

A.14.1.6 (i) Forward biased; (ii) Reversed Biased; (iii) Reversed Biased; (iv) Forward Biased.

A.14.1.7 No, n-type semiconductor does not have a net negative charge. This is because the donor atoms are also electrically neutral.

A.14.1.8 (i) The current across resistor R in circuit (i) is zero since diode D_2 is reversed-biased and hence offers infinite resistance. (ii) The current across resistor R in circuit (ii) is $3\text{ V}/30\ \Omega = 0.1\text{ A}$ since both diodes are forward biased and hence offer zero resistance.

A.14.1.9 (c) Since the diode will be forward biased in positive cycles, hence conducts. The diode is reverse biased in negative cycles and thus does not conduct, thus giving a potential difference between the output terminals.

14.1.6.5 Peak Inverse Voltage (PIV) rating of a diode

The maximum reverse bias potential that can be applied to a diode, before it 'enters' its breakdown region, is called its Peak Inverse Voltage. If a normal diode is operated above its PIV rating, it can burn or its junction properties can get lost. Therefore, before using a diode in reverse bias condition, its PIV rating should always be checked.

A diode can also be damaged even in forward bias if its maximum forward current and maximum power ratings are not taken care of.

14.1.7 Zener diode

Zener diode is a specially designed diode through its doping concentration. It is designed to operate in reverse bias in the breakdown region. In reverse bias, the current is very small and nearly constant with bias, termed as reverse saturation current. After a certain voltage, a small change in reverse bias voltage causes a large change in reverse current and the current suddenly increases (breakdown voltage, V_Z) in a Zener diode. The V - I characteristics are shown in Fig 14.1.24. This allows it to be operated in the breakdown region. In the breakdown region voltage remains nearly constant and hence it can be used as voltage regulator. Breakdown voltage is decided by the doping level.

Zener diodes are fabricated by heavily doping both p- and n- sides of the junction. Due to this, the depletion region formed is very thin. The order of the depletion layer can be $< 10^{-6}\text{m}$, and if a small reverse voltage, of say 5 V, is applied, then the order of electric field appearing across the junction would be

$$E = V/d \sim 5/10^{-6} \text{ V/m} \sim 5 \times 10^6 \text{ V/m}$$

Due to the existence of such a strong electric field, it is possible to initiate breakdown through a direct rupture of the covalent bonds. When this happens, a large number of charge carriers become available for conduction. The reverse voltage, at which breakdown gets initiated, is called the breakdown voltage (Fig 14.1.24). We know that reverse current is due to the flow of electrons (minority carriers) from p to n and holes from n to p. As the reverse bias voltage is increased, the electric field at the junction becomes significant. When the reverse bias voltage is increased, the electric field at the junction becomes significant.

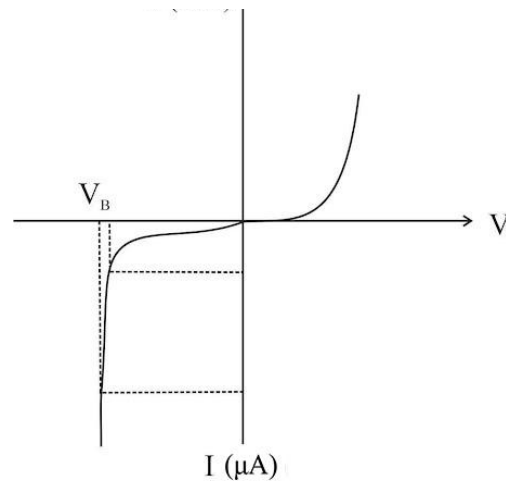


Fig 14.1.24 Typical V - I characteristics of a silicon diode

when the reverse bias voltage $V = V_Z$, then the electric field strength is high enough to pull valence electrons from the host atom on the p-side which are accelerated to n-side.

14.1.8 Summary

- Semiconductors are the basic materials used in the solid state electronic devices like diodes, transistors, Integrated Circuits (ICs), etc.
- Lattice structure and the atomic structure of constituent elements decide whether a particular material will be an insulator, metal, or a semiconductor.
- Metals have low resistivity (10^{-2} to 10^{-8} ohm-m), insulators have very high resistivity ($>10^8$ ohm-m⁻¹), while semiconductors have intermediate values of resistivity.
- 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 the '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, $n_e \gg n_h$ while in p-type semiconductors $n_h \gg n_e$.
- 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.
- $n_e n_h = n_i^2$ in all cases. Further, the material possesses 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 low 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 thus, produce a change in the current flowing in a semiconductor.
- For insulators $E_g > 3$ eV, for semiconductors E_g is 0.2 eV to 3 eV, while for metals $E_g \sim 0$.
- 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, junction barriers can be changed. In forward bias (n-side is connected to the negative terminal of the battery and the p-side is connected to the positive), the barrier is decreased while the barrier increases in reverse bias. Hence, the forward bias current is more (mA) while it is very small (μ A) in a p-n junction diode.
- The unique property of diodes is that they allow current to flow in one direction. This property of diodes is used in the rectifier. A rectifier is a device to convert alternating current into direct current.
- Zener diode is a specially designed diode through its doping concentration. It is designed to operate in reverse bias in the breakdown region. i.e. This property has been used to obtain *voltage regulation*.

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