CHAPTER : 27

SEMICONDUCTORS AND SEMICONDUCTING DEVICES

Ever since man moved out of the cave and settled into a civil society, his quest for comfort has increased continuously. The invention of fire and wheel proved turning points in human history. Probably, the next big development was the grey revolution, which transformed the way of communication, transportation and living. Sitting in our living rooms, we can connect to our loved ones face-to-face across oceans and continents using computer mediated video-conferencing.

To make all this possible solid state electronic devices have played a significant role. Electronics is a branch of science and technology in which electrons are manipulated to do some specific tasks. Scientists have studied the electrical nature of materials and developed a concept of **energy bands** in terms of which solids can be classified as conductors, semiconductors and insulators. Semiconductors are mostly used for developing electronic devices. Silicon and germanium are the most familiar semiconductor materials. Normally, the conductivity of a semiconductor lies in–between the conductivities of metals and insulators. However, at absolute zero, the semiconductor also acts like a perfect insulator. The conductivity of a semiconductor is influenced by adding some impurity element called *dopant.*

In this lesson you will learn about various types of semiconductors, their behaviour and how they are combined to form useful devices such as Zener diode, solar cell, photodiode, light emitting diode and transistor, etc. You will also learn to draw the I-V characteristics of Zener diode, LED, photo diode and solar cell.

OBJECTIVES

After studying this lesson, you should be able to :

- *explain what energy bands are and how they are used to classify materials as conductors, insulators and semiconductors;*

- *differentiate between (i) intrinsic and extrinsic and (ii) n-type and p-type semiconductors;*
- *explain formation of depletion region and barrier potential in a p-n junction diode;*
- *describe I-V characteristics of a p-n junction diode in the forward and reverse biases;*
- *describe different type of diodes, viz. zener, LED, photo diode and solar cell and their I-V characteristics;*
- *explain the action of a transistor;*
- *describe the effect of doping, size and function of different regions in a transistor;*
- *list the differences between p-n-p and n-p-n transistors;*
- *list different configurations in which a transistor can be connected and describe their input and output characteristics; and*
- *compare different configurations of a transistor in terms of their input/output resistance, gain and applications.*

28.1 ENERGY BANDS IN SOLIDS

While studying the structure of atoms you have learnt that electrons in an isolated atom stay in certain descrete, well defined energy states. When two atoms come closer to form a stable structure, such that the separation between them tends to be lesser than their diameter (d), the energy states tend to overlap, which is forbidden by Pauli's exclusion principle. Hence, they get modified and corresponding to each of the interaction energy states, two energy states are created: one slightly lower than the normal state which is called the bonding state and the other slightly higher than the normal state called the antibonding state.

In solids, very large number of atoms (typically 10^{23} atoms per cm^3) come together to form crystals. If N atoms interact corresponding to each of the energy states, 2N energy states are created. All these energy states are so close to each other (typically $\Delta E \sim 10^{-23}$ eV) that we cannot practically discriminate between them. This quasi continuous distribution of energy states, which are though separate but practically indiscriminable, is called **energy band**.

The process of interaction of energy states (and thereby energy band formation) starts from outer unfilled energy states and then proceeds to valence level. The band formed of unfilled energy levels is called conduction band and the one formed of filled valence levels is called valence band. The relative position of these bands, at equilibrium separation, determines the conduction characteristics of a solid.

28.1.1 Classification of Solids as Conductors, Semiconductors and Insulators on the basis of Energy Bands

If in a solid at equilibrium separation, the conduction band (CB) and valence bands (VB) overlap as it happens in case of metals the material is conductor [Fig. 28.1(a)].

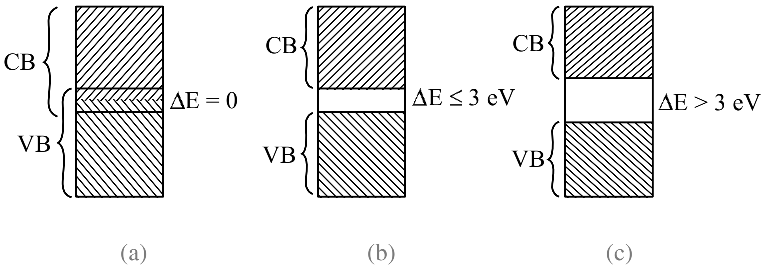


Fig. 28.1 Energy band in (a) Conductors (b) Semiconductors (c) Insulators

If at equilibrium separation the conduction band is completely empty, valence band is completely full and there is a small band gap ($\Delta E \leq 3$ eV) between the highest level of valence band and lowest level of conduction band, called a forbidden energy gap, the solid is a semiconductor. [Fig. 28.1(b)].

If at equilibrium separation, the CB is completely empty, VB is completely filled and there is a large band gap ($\Delta E > 3$ eV) the solid is an insulator.

28.2 INTRINSIC AND EXTRINSIC SEMICONDUCTORS

Semiconductors are classified on the basis of their purity as intrinsic (pure) and extrinsic (impure) semiconductors. Let us now learn about these.

28.2.1 An Intrinsic Semiconductor

Pure silicon and germanium are intrinsic semiconductors as the electrons in these elements are all tightly held in their crystalline structure, i.e., they do not have free electrons. When energy is added to pure silicon in the form of heat, say, it can cause a few electrons to break free of their bonds, leaving behind a hole in each case. (The absence of electrons is treated as positively charged particles having the same amount of positive charge as the negative charge on an electron.) These electrons move randomly in the crystal. These electrons and holes are called *free carriers,* and move to create electrical current. However, there are so few of them in pure silicon that they are not very useful.

Note that in an intrinsic semiconductor, electrons and holes are always generated in pairs and the negative charge of free electrons is exactly balanced by the positive charge of holes. However, a hole only shifts its position due to the motion of an electron from one place to another. *So we can say that when a free electron moves in a crystal because of thermal energy; its path deviates whenever it collides with a nucleus or other free electrons. This gives rise to a zig-zag or random motion, which is similar to that of a molecule in a gas.*

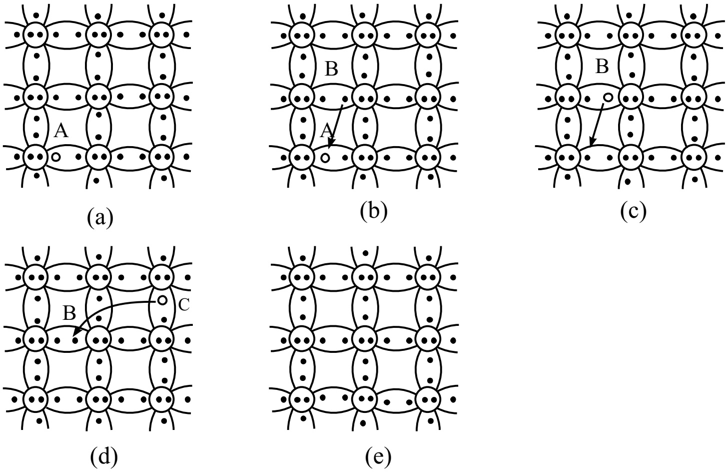


Fig. 28.2 : Movement of electrons and holes in a semiconductor

Now refer to Fig. 28.2(a) and consider the electron- hole pair generated at point *A*. The free electron drifts in the crystal leaving behind a hole. The broken bond now has only one electron and this unpaired electron has tendency to acquire an electron and complete its pair by forming a covalent bond. Due to thermal energy, the electron from neighbouring bond, say at point *B*, may get excited to break its own bond and jump into the hole at *A*. As a result, the hole at *A* vanishes and a new hole appears at *B* (Fig. 28.2(c)). Thus motion of electron from point *B* to point *A* causes the hole to move from *A* to *B*.

You may now like to ask: What will happen when hole at *B* attracts and captures a valence electron from neighbouring bond at *C*? The movement of electron from *C* to *B* causes movement of hole from *B* to *C* [see Fig. 28.2(d) and (e)]. Conventionally, the flow of electric current through the semiconductor is taken in the same direction in which holes move.

At absolute zero temperature, all valence electrons are tightly bound to their parent atoms and intrinsic semiconductor behaves as an insulator. At room temperature, the thermal energy makes a valence electron in an atom to move away from the influence of its nucleus. Therefore, a covalent bond is broken and electron becomes free to move in the crystal, resulting in the formation of a vacancy, called hole. ***Thus, due to thermal energy, some electron-hole pairs are generated and semiconductor exhibits small conductivity.*** For example, at room temperature (300 K), Ge has intrinsic carrier concentration of about $2.5\times 10^{19}\, m^{-3}$ electron-hole pair. As temperature increases, more electron-hole pairs are generated and conductivity increases. Alternatively, we can say that resistivity decreases as temperature increases. It means that semiconductors have negative temperature coefficient of resistance.

28.2.2 An Extrinsic Semiconductor

You now know that intrinsic semiconductors have high resistivity. Also their conductivity shows little flexibility. For these reasons, *intrinsic (pure) semiconductors are of little use; at best these can be used as a heat or light sensitive resistance.* These limitations are overcome by adding a small and measured quantity of another material to intrinsic (pure) semiconductor, which either increases the number of holes or electrons.

Note that the word impurity is being used here because we are adding atoms of some other element to a pure material.

The process in which some atoms of a pure or intrinsic semiconductor are replaced by impurity atoms from their lattice-sites is called **doping** and the impurity so added is called **dopant**. Such doped semiconductors are called **extrinsic** semiconductors.

The dopped semi-conductor normally belongs to group IV of periodic table and the dopants are generally taken from either **group III** (having three valence electrons) or **group V** (having five valence electrons) of the Periodic Table. Fig. 28.3 shows a small portion of the Periodic Table. Here groups III and V have been highlighted to indicate the types of materials generally used for doping.

II	III	IV	V	VI
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				

Fig. 28.3 : A part of the Periodic Table. Group III and V elements are used for doping an intrinsic semiconductor of group IV.

Normally we add a very small amount of impurity atoms to the pure simiconductor. It is of the order of one atom per 10^8 atoms of intrinsic semiconductor. These atoms change the balance of charge carriers; either they add free electrons or create holes. Either of these additions makes the material more conducting. Thus, most of the charge carriers in extrinsic semiconductors originate from the impurity atoms.

28.2.3 *n*-and *p*-type Semiconductors

From the electronic configuration of Si ($1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^2$), you will recall that ten electrons are tightly bound to the nucleus and four electrons revolve around the nucleus in the outermost orbit. In an intrinsic silicon semiconductor, the Si atom attains stability by sharing one electron each with four neighbouring Si atoms. (This is called *covalent bonding)*. The same holds true for germanium; its electronic configuration is $1s^2$, $2s^2$, $2p^6$, $3s^2$, $3p^6$, $3d^{10}$, $4s^2$, $4p^2$. When silicon (or germanium) is doped with a pentavalent (five electrons in the outermost orbit) atom like phosphorus, arsenic or antiomony, four electrons form covalent bonds with the four neighbouring silicon atoms, but the fifth (valence) electron remains unbound and is available for conduction, as shown in Fig. 28.4. Thus, when a silicon (or germanium) crystal is doped with a pentavalent element, it develops excess free electrons and is said to be an *n-type* semiconductor. Such impurities are known as *donor impurities.*

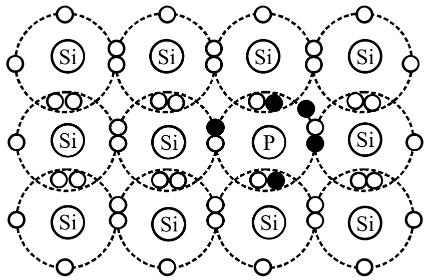


Fig. 28.4 : Covalent bonding in a *n*-type semiconductor

If silicon (or germanium) is doped with a trivalent (three electrons in the outermost shell) atom like boron, aluminium, gallium or indium, three valence electrons form covalent bonds with three silicon atoms and deficiency of one electron is created. This deficienty of electron is referred to as *hole.* It is shown in Fig. 28.5. Such a semiconductor is said to be a *p*-type semiconductor and the impurities are known as *acceptor impurities.*

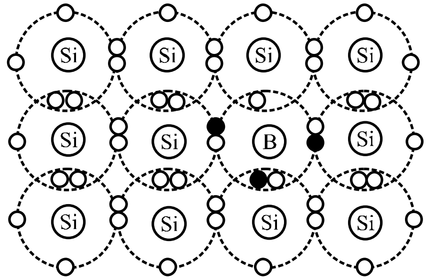


Fig. 28.5 : Colvalent bonding in a *p*-type semiconductor

You may now like to ask: Is a *n*-type semiconductor negatively charged or a p-type semiconductor positively charged? The answer to this question is not in affermative.

In fact, the number of free electrons is exactly equal to the total number of holes and positively charged ions and a semiconductor, whether intrinsic or doped, is electricially neutral.

Note that in a *p*-type semiconductor, more holes are created due to addition of acceptor impurity than by breaking covalent bonds due to thermal energy at room temperature. Hence, the net concentration of holes is significantly greater than that of electrons. That is, in a *p*-type semiconductor, the holes are the majority charge carriers. Similarly we can say that electrons are the majority charge carriers in n-type semiconductors.

INTEXT QUESTIONS 28.1

1. At 300 K, pure silicon has intrinsic carrier concentration of 1.5×10^{16} m^{-3}. What is the concentration of holes and electrons?
2. The *n*-type semiconductor is obtained by doping with
   (i) trivalent impurity
   (ii) pentavalent impurity
   (iii) tetravalent impurity
   (iv) trivalent as well as tetravalent
3. An intrinsic semiconductor can be converted into an extrinsic semiconductor by addition of .... This process in called ....
4. Electrons in *n*-type semiconductor and holes in *p*-type semiconductor are the .... carriers.
5. An extrinsic semiconductor has .... resistivity as compared to an intrinsic semiconductor.

28.3 A *p-n* JUNCTION

You now know that *n*-type and *p*-type semiconductors respectively have electrons and holes as majority charge carriers. What do you think will happen if a *n*-type material is placed in contact with a *p*-type material? Shall we obtain some useful device? If so, how? To answer such questions, let us study formation and working of a *p-n* junction.

28.3.1 Formation of *a p-n* Junction

To form a *p-n* junction, the most convenient way is to introduce donor impurities on one side and acceptor impurities into the other side of a single semiconducting crystal, as shown in Fig. 28.6.

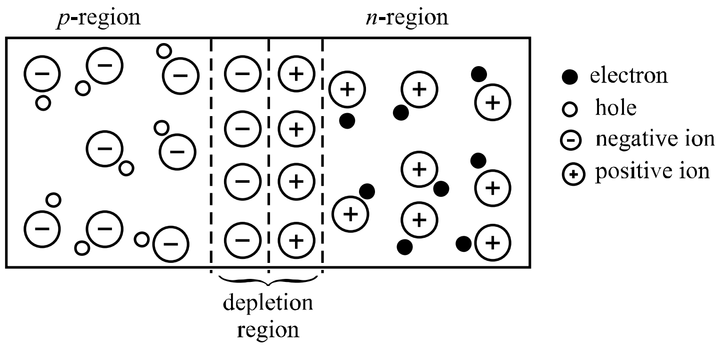


Fig. 28.6 : A p-n junction with depletion region

We now know that there is greater concentration of electrons in the *n*-region of the crystal and of holes in the *p*-region. Because of this, electrons tend to diffuse to the *p*-region and holes to the *n*-region and recombine. Each recombination eleminates a hole and a free electron. This results in creation of positively and negatively charged ions near the junction in *n* and *p* regions, respectively. As these charges accumulate, they tend to act as shield preventing further movement of electrons and holes across the junction. Thus, after a few recombinations, a narrow region near the junction is depleted in mobile charge carriers. It is about 0.5 μm thick and is called the *deplection region* or *space-charge region.*

Due to accumulation of charges near the junction, an electric field is established. This gives rise to electrostatic potential, known as *barrier potential.* This barrier has polarities, as shown in Fig. 28.7. When there is no external electric field, this barrier prevents diffusion of charge carriers across the junction.

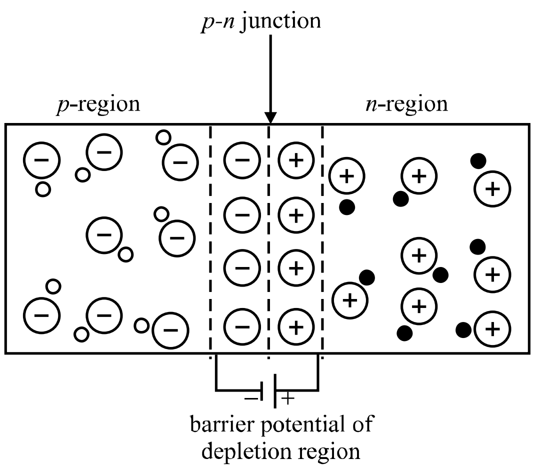
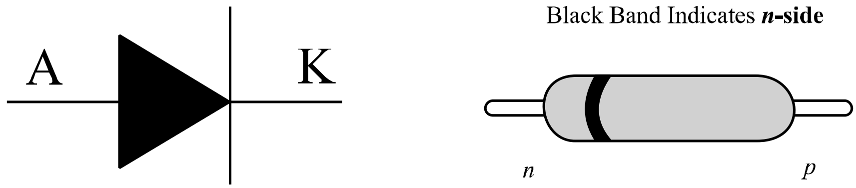


Fig.28.7 : Barrier potential due to depletion region

The barrier potential is characteristic of the semiconductor material. It is about 0.3 V for Ge and about 0.7 V for Si. The junction acts as a diode. It is symbolically represented as shown in Fig. 28.8(a). Here *A* corresponds to *p*-region and acts as an anode. Similarly, K indicates n-region and corresponds to a cathode. Fig 28.8 (b) shows a picture of p-n junction diode available in market.



(a) (b)

Fig. 28.8: (a) Symbol of a p-n junction (diode). The arrow gives the direction of conventional current. It is from p to n region **(b)** A p-n junction diode available in the market.

You may have noted that semiconductor diodes are designated by two letters followed by a serial number. The first letter indicates the material: *A* is used for material with a band gap of 0.6 eV to 1.0eV such as germanium. *B* is used for material with a band gap of 1.0eV to 1.3eV, such as silicon. The second letter indicates the main application: *A* signifies detection diode, *B* denotes a variable capacitance diode, *E* for tunnel diode, *Y* for rectifying diode and *Z* denotes Zener diode. The serial numbers specify power rating, peak reverse voltage, maximum current rating, etc. (We have to refer to manufacturer's catelogue to know exact details.) For example, *BY*127 denotes a silicon rectifier diode and *BZ*148 represents a silicon Zener diode.

To make visual identification of anode and cathode, the manufacturers employ one of the following ways :

- the symbol is painted on the body of the diode;
- red and blue marks are used on the body of the diode. Red mark denotes anode, whereas blue indicates the cathode;
- a small ring is printed at one end of the body of the diode that corresponds to the cathode. The band in Fig. 28.8(b) indicates the n-side of the p-n junction.

Note that we have to work within the specified ranges of diode ratings to avoid damage to the device.

INTEXT QUESTIONS 28.2

1. Fill in the blanks:

   (a) When a p-n junction is formed, the .... diffuse across the junction.

   (b) The region containing uncompensated acceptor and donor ions is called .... region.

(c) The barrier potential in silicon is .... V and in germanium, it is .... V.

(d) In a *p-n* junction with no applied electric field, the electrons diffuse from *n*-region to *p*-type region as there is .... concentration of .... in *n*-region as compared to *p*- region.

2. Choose the correct option:

(a) The potential barrier at the *p-n* junction is due to the charges on the either side of the junction. These charges are

(i) majority carriers

(ii) minority carriers

(iii) fixed donor and acceptor ions.

(iv) none of above

(b) In a *p-n* junction without any external voltage, the junction current at equillibrium is

(i) due to diffusion of minority carriers only

(ii) due to diffusion of majority carriers only

(iii) zero, as no charges are crossing the junction

(iv) zero, as equal and opposite charges are crossing the junction

(c) In a semiconductor diode, the barrier potential repels

(i) minority carriers in both the regions

(ii) majority carriers in both the regions

(iii) both the majority and the minority carriers

(iv) none of the above

3. Why is depletion region named so? What is depletion region made of?

28.4 FORWARD AND REVERSE BIASED *p-n* JUNCTION

Biasing means application of voltage. To make a *p-n* junction to conduct, we have to make electrons move from the *n*-type region to the *p*-type region and holes moving in the reverse direction. To do so, we have to overcome the potential barrier across the junction by connecting a battery to the two ends of the *p-n* junction diode. The battery can be connected to the *p-n* junction in two ways:

- Positive terminal of the battery connected to the *p*-side and negative terminal of the battery connected to the *n*-side. This is called **forward bias** [Fig. 28.9(a)].

- Positive terminal of the battery connected to the *n*-side and negative terminal of the battery connected to the *p*-side. This is called **reverse bias** [Fig. 28.9(b)].

When a junction is forward biased and the bias exceeds barrier potential, holes are compelled to move towards the junction and cross it from the *p*-region to the

n-region. Similarly, electrons cross the junction in the reverse direction. This sets in **forward current** in the diode. The current increases with voltage and is of the order of a few milliampere. Under the forward bias condition, the junction offers low resistance to flow of current. Can you guess its magnitude? The value of junction resistance, called **forward resistance,** is in the range 10Ω to 30Ω.

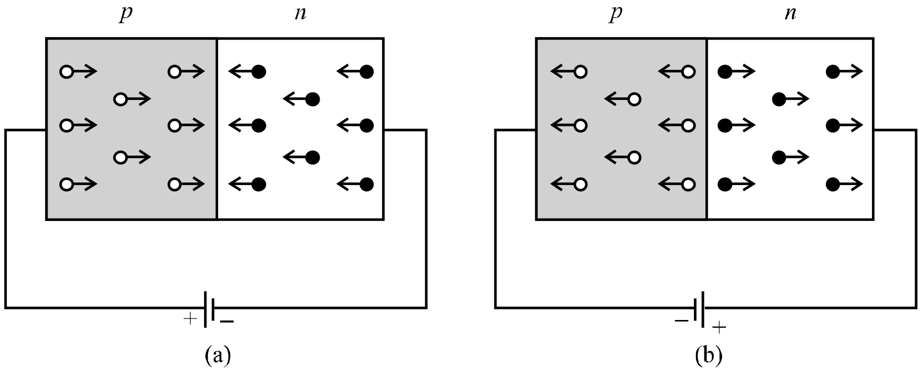


Fig. 28.9 : (a) Forward biased, and **(b)** reverse biased *p-n* junction

When the *p-n* junction is **reverse biased,** holes in the *p*-region and electrons in the *n*-region move away from the junction. Does it mean that no current shall flow in the circuit? No, a small current does flow even now because of the fewer number of electron-hole pairs generated due to thermal excitations. This small current caused by minority carriers is called **reverse saturation current** or **leakage current.** In most of the commercially available diodes, the reverse current is almost constant and independent of the applied reverse bias. Its magnitude is of the order of a few microamperes for Ge diodes and nanoamperes in Si diodes.

A *p-n* junction offers low resistance when forward biased, and high resistance when reverse biased. This property of *p-n* junction is used for ac rectification.

When the reverse bias voltage is of the order of a few hundred volt, the current through the *p-n* junction increases rapidly and damages it due to excessive power dissipation. The voltage at which a diode breaks down is termed as **breakdown voltage.** Physically, it can be explained as follows: When a reverse bias is applied, a large electric field is established across the junction. This field (i) accelerates the available minority carriers, which, in turn, collide with the atoms of the semiconductor material and eject more electrons through energy transfer (avalanche effect), and (ii) breaks covalent bonds by exerting large force on electrons bound by the bonds. This results in creation of additional electron-hole pairs in the junction region (Zener effect). Both these processes give rise to large reverse current even for a small increment in reverse bias voltage. This process is termed as *Zener breakdown.*

INTEXT QUESTION 28.3

1. Define forward bias.
2. Define reverse bias.
3. Fill in the blanks:
   (a) When forward bias is applied on a *p-n* junction diode, the width of the depletion region ....
   (b) When a *p-n* junction diode is reverse biased, the width of depletion region
   (c) When the reverse bias voltage is made too high, the current through the *p-n* junction .... abruptly. This voltage is called.
4. Choose the correct option:
   (a) In a forward biased junction
      (i) the holes in the *n*-region move towards the *p*-region
      (ii) there is movement of minority carriers
      (iii) charge carriers do not move
      (iv) majority carriers in both the regions (*n* and *p*-regions) move into other regions.
   (b) In a reverse biased junction
      (i) there is no of potential barrier
      (ii) there is movement of majority carriers only
      (iii) there is movement of minority carriers only
      (iv) none of the above
5. State two types of reverse breakdowns which can occur in a *p-n* junction diode and differentiate between them.

28.5 CHARACTERISTICS OF *p-n* JUNCTION DIODES

The practical application of a semiconductor device in electronic circuits depends on the current and voltage (*I-V*) relationship, as it gives vital information to a circuit designer as well as a technician. Therefore, with the help of *I–V* characteristics, we can know how much current flows through the junction diode at a particular voltage.

28.5.1 Forward Bias Characteristics

Refer to Fig. 28.10(a). You will note that to draw forward bias characterstic of a *p-n* junction diode, the positive terminal of a battery (*B*) is connected to *p*-side of the diode through the rheostat. (Alternative by we can use a variable battery.) The voltage applied to the diode can be varied with the help of the rheostat. The milliammeter (*mA*) measures the current in the circuit and voltmeter (*V*) measures the voltage across the diode. The direction of conventional current is the same as the direction of the diode arrow. Since current experiences little opposition to its flow through a forward biased diode and it increases rapidly as the voltage is increased, a resistance (*R*) is added in the circuit to limit the value of current. If this resistance is not included, the diode may get permanently damaged due to flow of excessive current through it.

The *I-V* characteristic curve of a *p-n* junction in forward bias is shown in Fig. 28.10(b).

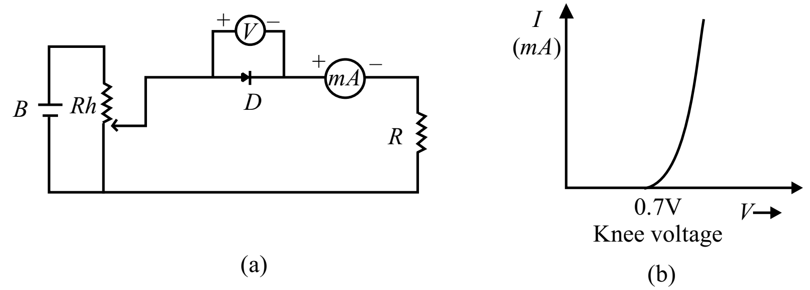


Fig. 28.10 : (a) Circuit diagram *I-V* characteristics of a *p-n* junction diode in forward bias, and **(b)** typical characterstics curve.

Note that the characteristic curve does not pass through origin; instead it meets the *V*-axis at around 0.7V. It means that the *p-n* junction does not conduct until a definite external voltage is applied to overcome the barrier potential. The forward voltage required to get the junction in conduction mode is called **knee voltage.** It is about 0.7 V for Si and 0.3 V for Ge *p-n* junction.

This voltage is needed to start the hole-electron combination process at the junction. As the applied voltage is increased beyond knee voltage, the current through the diode increases linearly. For voltage of around 1V, the current may attain a value of 30-80 mA.

28.5.2 Reverse Bias Characteristics

To draw reverse bias characteristics of a *p-n* junction, we use the circuit diagram shown in Fig. 28.11 (a). If you compare it with Fig. 28.10(a) for forward *I-V* characteristics, you will note two changes:

(i) The terminals of the junction are reversed.

(ii) Instead of milliammeter, microammeter (μ A) is used.

A typical *I-V* characteristic curve of a *p-n* junction in reverse bias is shown in Fig 28.11(b).

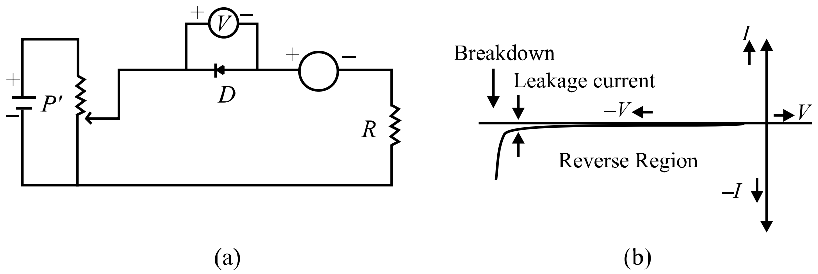


Fig.28.11 : a) Circuit diagram to obtain *I-V* characteristics of a *p-n* junction in reverse bias, and **b)** reverse bias characteristic curve

Note that the junction current is comparatively much less in reverse bias for all voltages below the breakdown voltage. And at breakdown voltage, the current increases rapidly for a small increase in voltage. Moreover, comparison of Fig. 28.10(b) and 28.11(b) reveals that a *p-n* junction diode offers low resistance when it is forward biased and high resistance when reverse biased. At the breakdown voltage in reverse biased *p-n* junction diode, the sharp increase in reverse current is due to sudden decrease in resistance offered by the junction.

From this we may conclude that a *p-n* junction diode conducts in only one direction, i.e. has unidirectional conduction of current, with electrons flowing from the *n*-type region to *p*-type end in forward bias.

You may have seen turnstiles at a metro subway station that let people go through in only one direction. A diode is a one-way turnstile for electrons.

p-n junction diodes find wide applictions. These include :

1. The unidirectional conducting property of a diode is used to convert ac voltage into dc voltage as a *rectifier*. Diodes are also used in adaptors to recharge batteries of cell phones, CDplayers, laptops, etc. You will study about it in detail in the next lesson.
2. A device that uses batteries often contains a diode as it simply blocks any current from leaving the battery, if it is reverse biased. This protects the sensitive electronics in the device.

INTEXT QUESTIONS 28.4

1. Explain the concept of knee voltage.
2. (a) The knee voltage in case of silicon diode is .... whereas in germanium diode it is ....

   (b) In a *p-n* junction diode, the current flows only in .... direction.

   (c) The reverse saturation current is of the order of .... for germanium diodes.

3. Choose the correct option :

(a) The *I-V* characteristics of a *p-n* junction diode in forward bias show

(i) a non-linear curve

(ii) linear curve

(iii) linear as well as non-linear portions

(iv) none of above

(b) When a *p-n* junction is forward biased and the voltage is increased, the rapid increase in current for relatively small increase in voltage occurs

(i) almost immediately

(ii) only when the forward bias exceeds the potential barrier

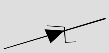
(iii) when there is breakdown of the junction

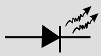
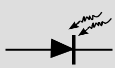
(iv) none of the above

28.6 TYPES OF DIODES

By adjusting the levels of doping, doping material and the geometry (size, area etc.) of a *p-n* junction diode, we can modify its electrical and optical behaviour. In this section, we have listed diodes whose properties have been deliberately modified to obtain specific capabilities. Each of these diodes has its own schematic symbol and reflects its nature and functions.

You can use the following table to make a comparison between different diodes:

Name	Symbol	Construction	Principle mechanism	Main	Main use function
Zener diode		*p-n* junction diode with heavily doped *p-* & *n-* regions. Very narrow depletion layer (< 10 nm).	Zener breakdown mechanism	Provides continuous current in reverse breakdown voltage region without being damaged.	Voltage stabilization or regulation
Photo-diode		*p-n* junction diode. Uses light (or photo) emitting semicon-ductor materials, with very thin *p*-region, whose thickness is determined by wavelength of radi-ation to be detected	Photovoltaic effect into electrical current in	Converts an optical input controls in VCR & TV reverse bias.	Receivers for remote

LED		*p-n* junction diode with materials having band energies correspoding to near infrared region or visible light region (GaAsP or InP)	Electrolu minous	Changes an electrical inputto a light output in forward bias.	Used in multimeters, digital watches, instrument displays, calculators, switch boards, burglar alarm and remote control devices
Solar cell		*p-n* junction diode in which either *p* or *n* region is made very thin to avoid significant absorption of light before reaching the junction	Photovoltaic effect	Conversion of solar energy into electrical energy	1. In satellites to power systems. 2. To charge batteries. 3. Calculators

28.6.1 I–V Characteristics of Zener diode

Zener diode is fabricated by heavily doping both the *p*- and *n*-sides of the junction. Hence depletion layer formed is very thin $(< 10^{-6}\ \text{m})$. And the electric field across the depletion layer is extremely high $(\sim 5\times 10^{6}\ \text{N C}^{-1})$ even for a small reverse bias voltage of 5 V. The I-V characteristics of a Zener diode is shown in Fig. 28.12. It is seen that when the applied reverse voltage (V) reaches the breakdown voltage (V_z) of the Zener diode, there is a large change in the current. After the breakdown voltage v_z, a large change in the current can be produced by almost insignificant change in the reverse bias voltage. Zener voltage remains constant, even though the current through the Zener diode varies over a wide range.

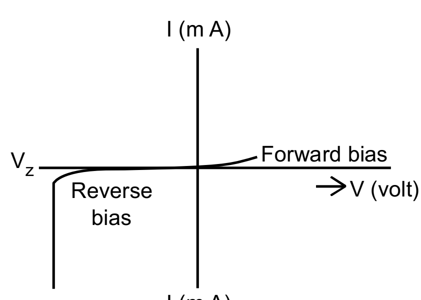


Fig. 28.12

28.6.2 I-V Characteristics of light-emitting diode

In light-emitting diode (LED) when the forward current of diode is small the intensity of light emitted is small. As the forward current increases, the intensity of the emitted light increases and reaches a maximum value. Further increase in the forward current results in a decrease of light intensity. LEDs are biased such that the light emitting efficiency is maximum.

The I-V characteristics of a LED is similar to that of a Si junction diode as shown in Fig. 28.13. But the threshold voltages are much higher and slightly different for each colour. The reverse breakdown voltage of LEDs are very low, typically around 5V.

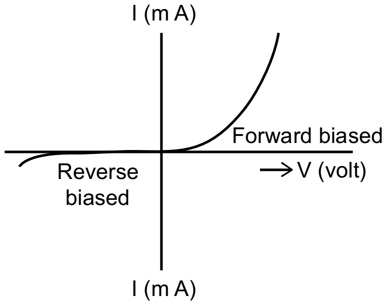


Fig. 28.13

28.6.3 I-V Characteristics of Photo diode

The photo diode is fabricated such that the generation of electron – hole pairs takes place in or near the depletion region in the diode. Due to the electric field of the junction, the electrons and holes are separated before they recombine. The direction of the electric field is such that the electrons reach the *n*-side and the holes reach the *p*-side. The electrons are collected on the n-side and the holes are collected on the *p*-side giving rise to an emf. When an external load is connected, the current flows. The magnitude of the photocurrent depends on the intensity of the incident light.

I-V Characteristics of a photo diode are shown in Fig. 28.14.

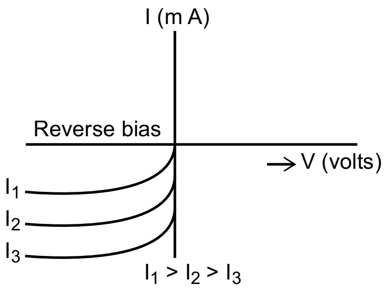


Fig. 28.14

28.6.4 I-V Characteristics of Solar Cell

The generation of emf, when the light falls on a solar cell is due to the following three basic processes: generation, separation and collection. Generation of electron – hole pairs is due to the light (with $h\nu > E_g$) close to the junction. Separation of electrons and holes is due to the electric field of the depletion layer. Electrons are swept to the *n*-side and the holes to the *p*-side.

The electrons reaching the *n*-side are collected by the front contact and the holes reaching the *n*-side are collected by the back contact. Thus the *p*-side becomes positive and the *n*-side negative giving rise to photo voltage.

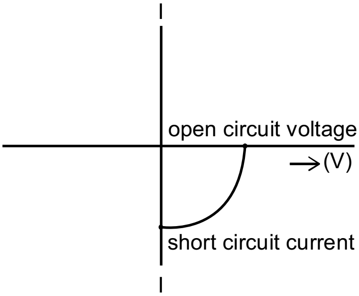


Fig. 28.15

The I-V characteristic curves of a solar cell are shown in Fig. 28.15. They are drawn in the fourth quadrant of the coordinate axis. This is because a solar cell does not draw current but supplies the same to the load.

INTEXT QUESTIONS 28.5

1. Choose the correct option

   (a) A zener diode is operated in

   (i) Forward bias

   (ii) Reverse bias

   (iii) Both of the above

   (iv) None of the above

   (b) Zener dide is

   (i) A highly doped *p-n* junction diode

   (ii) A lowly doped *p-n* junction diode

   (iii) A moderately doped *p-n* junction diode

   (iv) Another name of normal *p-n* junction diode

   (c) A zener diode is used as a

   (i) amplifier

   (ii) rectifier

   (iii) constant current device

   (iv) constant voltage device

2. Fill in the blanks

   a) The zener diode is based on the .... breakdown mechanism.

   b) A photodiode is operated in .... bias.

   c) In a photodiode, the *p-n* junction is made from .... semiconductor material.

   d) LED's are made up of the conductor material from .... of the periodic table.

   e) The light emitting diodes operate in .... bias.

   f) The .... arrow in the symbol of LED symbolizes .... of light.

   g) In an LED light is emitted due to .... of electrons and holes.

   h) LED is based on the principle of ....

   i) Solar cells are based on .... effect.

   j) When sunlight having energy .... than the band gap energy falls on the solar cell, it is .... and frees electron-hole pairs.

3. How does the separation of electrons and holes take place in a solar cell?

28.7 TRANSISTORS – *pnp* AND *npn*

In the preceeding sections, you have learnt about a *p-n* junction diode, which permits current to flow in only one direction. This limits its applications to rectification and detection. A more useful semiconductor device is a bipolar junction transistor.

The invention of transistor by John Bardeen, Walter Brattain and William Shockley in 1948 at Bell laboratory in USA revolutionised the electronic industry. The transistors find many any varied uses in our daily life ranging from gas lighter to toys to amplifiers, radio sets and television. In the form of switching device, these can be used to regulate vehicular traffic on the roads. They form key elements in computers, space vehicles, power systems in satellites and communication.

A transistor is basically a silicon or germanium crystal containing three alternate regions of *p* and *n*-type semiconductors as shown in Fig. 28.16. These three regions are called *emitter*(*E*), *base*(*B*) and *collector*(*C*). The middle region is the base and the outer two regions are emitter and collector. Note that the emitter and collector are of the same type (*p* or *n*) and collector is the largest of the three regions.

The base terminal controls the current flowing between the emitter and the collector. This control action gives the transistor an added advantage over the diode, which has no possibility of controlling the current flow. Depending on the type of doping, the transistors are classified as *n-p-n* or *p-n-p*. In general, the level of doping decreases from emitter to collector to base.

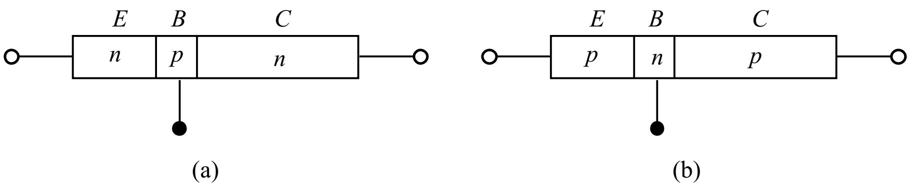
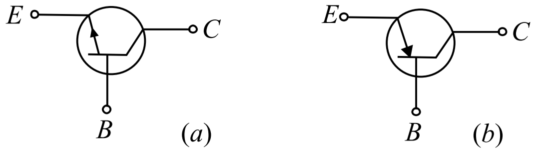


Fig. 28.16 : (a) *n-p-n,* and **(b)** *p-n-p* transistor

The names of the terminals of a transistor give clear indication of their functions. In case of a *n-p-n* transistor, the majority carriers (electrons) from the emitter are injected into base region. Since base is a very lightly doped thin layer, it allows most of the electrons injected by the emitter to pass into the collector. Being the largest of three regions, the collector dissipates more heat compared to the other two regions.



Figs 28.17 : Symbols of **a)** *n-p-n,* and **b)** *p-n-p* transistors

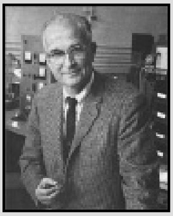
The symbolic representations of *n-p-n* and *p-n-p* transistors are shown in Fig. 28.17. The arrow head indicates the direction of flow of conventional current.

You may now like to ask : Why does the arrow head point outward in case of *n-p-n* transistor and inward in case of *p-n-p* transistor?

In a *n-p-n*, transistor, the emitter current is due to flow of electrons from emitter to base, and the conventional current flows from base to emitter and hence the arrow head points out from the base. In case of *p-n-p* transistor, the emitter current comprises flow of holes from emitter to base. Thus the conventional current flows from emitter to base.

Since transistors are bipolar devices, their operation depends on both the majority and minority carriers.

William Bradford Shockley
(1910 – 1989)



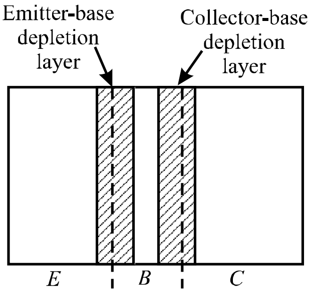
England born, American physicist W.B. Shockley was one of the three scientists who received 1956 Nobel Prize in physics for the discovery of transistor. Basically a solid state physicist, shockley contributed significantly to the development of theoretical understanding of bands in semiconductors, order and disorder in alloys; theory of vacuum tubes, theory of dislocations and theory of ferromagnetic domains. He is truely one of the pioneers of electronic revolution.

28.7.1 Working Principle

You are familiar with the working of a *p-n* junction. We now discuss the working principle of a transistor and consider an *n-p-n* transistor first because it is more commonly used.

When no voltage is applied across the transistor, diffusion of free electrons across the junctions produces two depletion layers, as shown in Fig. 28.18. For each depletion layer, the barrier potential is about 0.7V at 25°C for a silicon transistor and 0.3V for a germanium transistor. As you may be aware, silicon transistors are more widely used than germanium transistors because of higher voltage rating, greater current ratings, and low temperature sensitivity. For our discussion, we refer to silicon transistors, unless otherwise indicated.

Since the three regions in a transistor have different doping levels, the depletion layers have different widths. If a region is heavily doped, the concentration of ions near the junction will be more, resulting in thin depletion layer and vice versa. Since the base is lightly doped as compared to emitter and collector, the depletion layers extend well into it, whereas penetration in emitter/collector regions is to a lesser extent (Fig. 28.18). Moreover, the emitter depletion layer is narrower compared to collector depletion layer.



Figs 28.18: Depletion layers in a transistor when no voltage is applied

In order to made a transistor funciton properly, it is necessary to apply suitable voltages to its terminals. This is called **biasing** of the transistor.

A *n-p-n* Transistor

A typical biasing scheme of a *n-p-n* transistor is shown in Fig. 28.19(a). Note that *the emitter-base junction is forward biased while the collector-base junction is reverse biased.* We therefore expect a large emitter current and low collector current. But in practice, we observe that the collector current is almost as large as the emitter current. Let us understand the reason. When forward bias is applied to the emitter, free electrons in the emitter have to overcome the barrier potential to enter the base region [see Fig. 28.19(b)]. When V_{BE} exceeds barrier potential (0.6 to 0.7V for silicon transistor), these electrons enter the base region, as shown in Fig. 28.19(c). Once inside the base, these electrons can flow either through the thin base into the external base lead or across the collector junction into the collector region. The downward component of base current is called *recombination current*. It is small because the base is lightly doped and only a few holes are available. Since the base region is very thin and it receives a large number of electrons, for $V_{BE} > 0.7V$, most of these electrons diffuse into the collector depletion layer. The free electrons in this layer are pushed (by the depletion layer field) into the collector region [(Fig. 28.19(d)] and flow into the external collector lead. So, we can say that a steady stream of electrons leaves the negative source terminal and enters the emitter

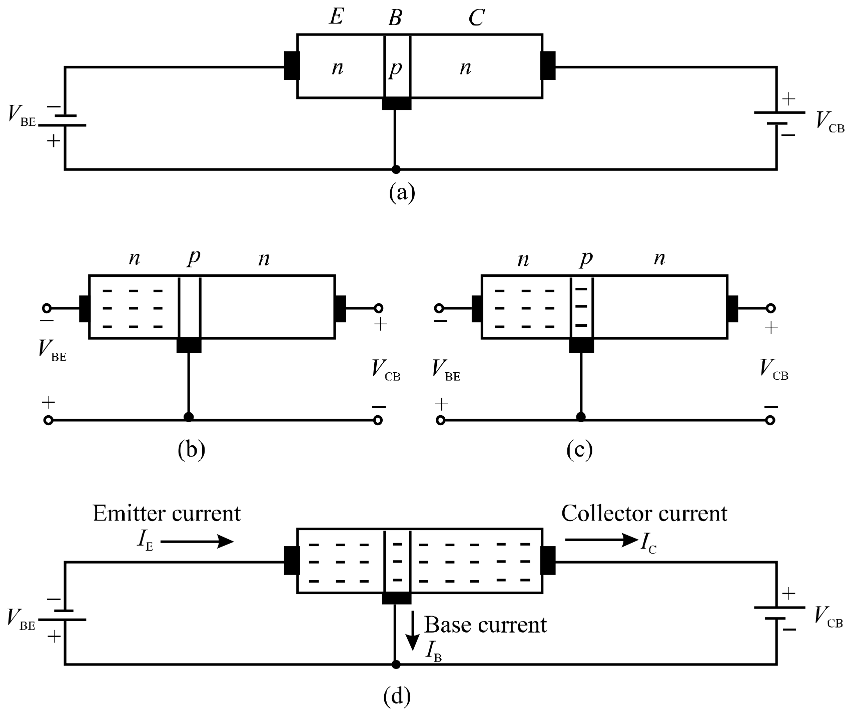


Fig. 28.19 : A *n-p-n* transistor when **(a)** emitter is forward-biased and collector is reverse-biased, **(b)** free electrons in an emitter, **(c)** free electrons injected into base; and **(d)** free electrons pass through the base to the collector.

region. The forward bias forces these electrons to enter the base region. Almost all these electrons diffuse into the collector depletion layer through the base. The depletion layer field then pushes a steady stream of electrons into the collector region. In most transistors, more than 95 percent emitter-injected electrons flow to the collector; less than 5 percent flow to the external base lead.

From this you should not conclude that you can connect two discrete diodes back to back to get a transistor. This is because in such a circuit, each diode has two doped regions and the overall circuit would have four doped regions and the base region would not be the same as in a transistor. *The key to transistor action, therefore, is the lightly doped thin base between the heavily doped emitter and the intermediately doped collector*. Free electrons passing through the base stay in base for a short time and reach the collector.

The relation between collector current (I_C) and emitter current (I_E) is expressed in terms of signal current gain, α, of a transistor. It is defined as

$$\alpha = \frac{I_C}{I_E}. \qquad (28.1)$$

You should note that the value of α is nearly equal to but always less than one.

Similarly, we can relate the collector current to the base current in a transistor. It is denoted by greek letter beta:

$$\beta = \frac{I_C}{I_B} \qquad (28.2)$$

Beta signifies the current gain of the transistor in common-emitter configuration. The value of β is significantly greater than one.

Since emitter current equals the sum of collector current and base current, we can write

$$I_E = I_C + I_B$$

On dividing throughout by I_C, we get

$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C}. \qquad (28.3)$$

In terms of α and β, we can rewrite it as

$$\frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

or

$$\beta = \frac{\alpha}{1-\alpha} \qquad (28.4)$$

Let us now consider how a *p-n-p* transistor differs from a *n-p-n* transistor in its details.

A *p-n-p* Transistor

A *p-n-p* transistor biased for operation in the active region is shown in Fig 28.20. Note that we reverse the battery terminals when *n-p-n* transistor is substituted by *p-n-p* transistor.

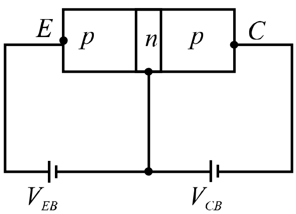


Fig. 28.20 : A p-n-p transistor biased for active operation

As before, the emitter - base junction is forward biased by battery of voltage V_{EB} and the collector base junction is reverse biased by a battery of voltage V_{CB}. The resistance of the emitter-base junction is very small due to its forward bias as compared to the collector-base junction (which is reverse biased). Therefore, we apply small forward bias voltage (0.6V) to the emitter-base junction, whereas the reverse bias voltage applied to the collector-base junction is of much higher value (9V).

The forward bias of emitter-base junction makes the majority carriers, that is the holes, in emitter (*p*-region), to diffuse to the base (*n*-region), on being repelled by the positive terminal of the battery. As width of the base is extremely thin and it is lightly doped, very few (two to five percent) of total holes that enter the base recombine with electrons and 95% to 98% reach the collector region. Due to reverse bias of the collector- base region, the holes reaching this region are attracted by the negative potential applied to the collector, thereby increasing the collector current (I_C). Therefore, increase in emitter current (I_E) increases collector current. And Eqns. (28.1) – (28.4) hold in this case as well.

INTEXT QUESTION 28.6

1. Choose the correct option:
   (a) The arrow head in the symbol of a transistor points in the direction of
      (i) hole flow in the emitter region
      (ii) electron flow in emitter region
      (iii) majority carriers flow in the above region
      (iv) none of the above
   b) The emitter current in a transistor in normal bias is
      (i) less than the collector current
      (ii) equal to sum of base current and collector current
      (iii) euqal to base current
      (iv) none of the above
2. Fill in the blanks
   (a) A ransistor has .... regions and .... junctions.
   (b) In a transistor, ... has the least thickness.
   (c) The emitter region is .... doped, whereas .... region has the least doping.
   (d) The collector of the transistor has .... size and .... doping.

(e) The transistor is said to be in active region when .... junction is forward biased and .... junction is reverse biased.

(f) The two types of transistors are .... and ....

You now know the working principle of a transistor. Let us learn the various ways in which a transistor is biased.

28.7.2 Transistor Configurations

A transistor is a two-port device; it can take an input and deliever an output. For both input and output, two terminals are needed. This can be done in a transistor by making one of the three terminals common. The configurations of a transistor in which one of the terminals is common to both input and output are shown in Fig. 28.21.

- When emitter is common to both input and output circuits, we obtain common emitter (*CE*) configuration (Fig. 28.21a);
- When base is common to both input and output circuits, we obtain common base (*CB*) configuration (Fig. 28.21b); and
- When collector is common to both input and output circuits, we have common collector (*CC*) configuration (Fig.28.21c).

In each of these configurations, the transistor characteristics are unique. The *CE* configuration is used most widely because it provides voltage, current and power gains. In the *CB* configuration, the transistor can be used as a constant current source while the *CC* configuration is usually used for impedance matching.

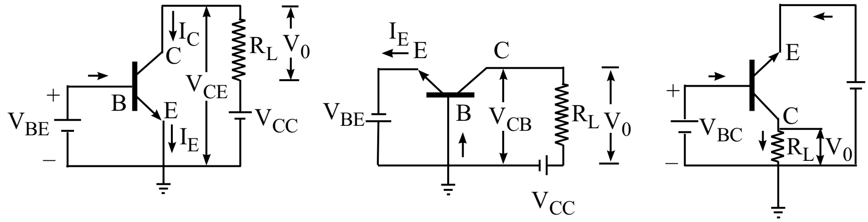


Fig. 28.21: Transistor configuration: **a)** *CE*, **b)** *CB*, and **c)** *CC*

For each configuration, we can plot three different characteristics: a) input characteristics, b) output characteristics, and c) transfer characteristics, depending on the nature of quantities involved.

Table 28.2 gives various quantities related to each of these characteristics in all the three configurations and the transistor constants of interest.

Table 28.2: Physical quantities of interest in different characteristics of a transistor

Configuration	Input Characteristic	Output characteristic	Transfer characteristic	Important transistor constant
CE	V_{BE} and I_B with V_{CE} as parameter	V_{CE} and I_C with I_B as parameter	I_B and I_C	Current gain, β
CB	V_{BE} and I_E with V_{CB} as parameter	V_{CB} and I_C with I_E as parameter	I_E and I_C	Large signal current gain, α
CC	V_{CB} and I_B with V_{CE} as parameter	V_{CE} and I_E with I_B as parameter	I_B and I_E	

To work with a transistor, you will be required to identify its base, emitter and collector leads. To do so, you can follow the following steps.

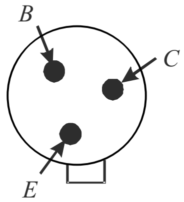


Fig. 28.22 : Identifying transistor leads.

Look for the a small notch provided on the metallic cap. The terminal close to the notch is emitter. To identify other two terminals, turn the transistor up-side-down. You can easily identify the base and the collector as shown in Fig. 28.22.

Like a *p-n* junction diode, transistors are also designated with two letters followed by a serial number. The first letter gives an indication of the material. *A* is for germanium and *B* is for silicon. The second letter indicates the main application: *C* is used for audio frequency transistors, *D* for power transistors and *F* for radio-frequency transistors. The serial number consists of digits assigned by the manufacturer for identification. For example, *AC* 125 represents germanium transistor for *AF* applications.

28.8 TRANSISTOR CHARACTERISTICS

As mentioned earlier, operation of a transistor can be studied with input and output *I-V* characteristics. The nature of these characteristics is unique and depends on the configuration used. Let us first study *CE* configuration.

28.8.1 Common Emitter (*CE*) Configuration of a *npn* Transistor

Common emitter characteristics of a transistor relate voltage and current when emitter is common to both input and output circuits. The circuit diagram for *CE* characteristics of a *n-p-n* transistor is shown in Fig. 28.23. V_{BB} is a variable *dc* supply of 0-3V and V_{CC} is a variable *dc* supply of 0-15V. R_1 and R_2 are potentiometers and R is a variable resistor. It is used to control base to emitter voltage, V_{BE}.

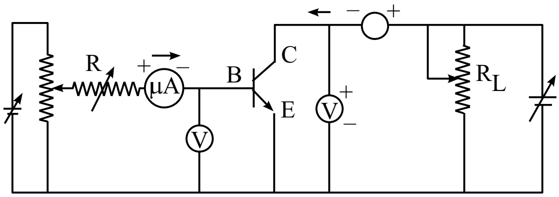


Fig. 28.23 : Circuit diagram for input and output characteristics of a transistor in *CE* configuration.

Input characteristics

In *CE* configuration, the input characteristics show the variation of I_B with V_{BE} when V_{CE} is held constant. To draw this characteristic, V_{CE} is kept at a suitable value with the help of R and R_1. Then V_{BE} is changed in steps and corresponding values of I_B are measured with the help of microammeter, connected to base. Fig. 28.24. shows typical input characteristics of a *n–p-n* transistor in *CE* configuration.

Note that for a given value of V_{CE}, the curve is as obtained for forward biased *p-n* junction diode. For $V_{BE} < 0.5$V, there is no measurable base current ($I_B = 0$). However, I_B rises steeply for $V_{BE} > 0.6$V.

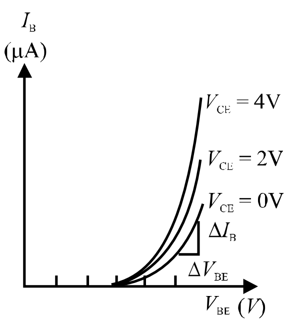


Fig. 28.24 : Input characteristics of a typical *npn* transistor in *CE* configuration

From the reciprocal of the slope of input characteristic, we get input resistance of the transistor defined as the ratio of small change in base - emitter voltage to the small change produced in the base current at constant collector - emitter voltage:

$$R_{ie} = \left.\frac{\Delta V_{BE}}{\Delta I_B}\right|_{V_{CE}} \qquad (28.5)$$

Usually, the value of R_{ie} is in the range 20-100Ω. You should note that since the curve is not linear, the value of input resistance varies with the point of measurement. As V_{CE} increases, the curve tends to become more vertical and the value of R_{ie} decreases.

Output characteristics

The output characteristic curves depict the variation of collector current I_C with V_{CE}, when base current I_B is kept constant. To draw output characteristics, I_B is fixed, say at 10 μA, by adjusting R_1 and R. V_{CE} is then increased from 0 to 10 V in steps of 0.5V by varrying R_2 and the corresponding value of I_C is noted. Similarly, the output characteristics can be obtained at I_B = 40μA, 60μA, 80μA. However, in no case, the maximum base current rating of the transistor should be exceeded.

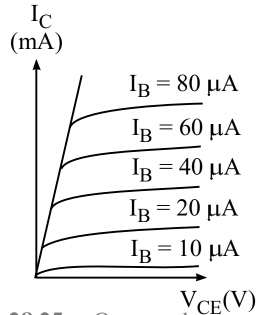


Fig. 28.25 : Output characteristics of a typical *npn* transistor in CE configuration

The output characteristics of this configuration are shown in Fig. 28.25.

From the output characteristics, you will note that I_C changes with increase in V_{CE} for a given value of I_B and I_C increases with I_B for a given V_{CE}. *From these characteristics, we can calculate output admittance* (h_{oe}):

$$h_{oe} = \frac{\Delta I_C}{\Delta V_{CE}} \tag{28.6}$$

where Δ denotes a small change.

28.8.2 Common Emitter (*CE*) Configuration of a *pnp* Transistor

In the preceding section, you learnt to draw input and output characterstics of a *n-p-n* transistor in common emitter configuration. Now we will consider a *p-n-p* transistor. Fig. 28.26 shows the circuit diagram for *CE* characteristics of a *p-n-p* transistor. The transistor is biased to operate in the active region. The microammeter and voltmeter are used in the base- emitter circuit to measure the base current (I_B) and the voltage between base and emitter. Similarly, milliammeter and voltmeter are connected in collector-emitter circuit to measure the collector current (I_C) and voltage between collector and emitter (V_{CE}).

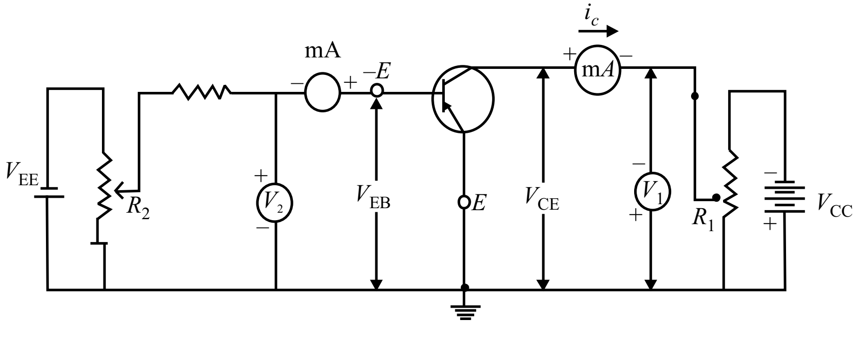


Fig. 28.26 : Circuit diagram for obtaining input and output characteristics of a *p-n-p* transistor in *CE* configuration

Input Characteristics

Input characteristics are graphs between V_{BE} and I_B at different constant values of V_{CE}.

To plot input characteristics, the potentiometer R_1 in the emitter- collector circuit is adjusted till the voltmeter shows constant value. Then potentiometer in the emitter-base circuit is adjusted in such a way that base-emitter voltage is zero. For this value, base current is also observed to be zero. Keeping the V_{CE} constant, V_{BE} is increased gradually and change in base current is noted with the help of microammeter. To plot input characteristics at $V_{CE} = -2V$, say, the potentiometer in emitter-collector circuit is adjusted till the voltmeter in the same circuit reads 2V. Then potentiometer in the emitter -base circuit is adjusted to make V_{BE} zero. Then V_{BE} is increased gradually, keeping V_{CE} constant. Similarly the input characteristics of the transistor in the CE configuration can be drawn for different values of V_{CE} = – 6V, 1V and so on. Fig. 28.27 shows typical input characteristics of *CE* configuration. As may be noted, the nature of *input characteristics is similar to the forward characteristics of p-n junction diode*. The base current remains zero as long as the base voltage is less than the barrier voltage (for silicon transistor, it is ~0.7V). As the base voltage exceeds barrier voltage, current begins to increase slowly and then rises abruptly.

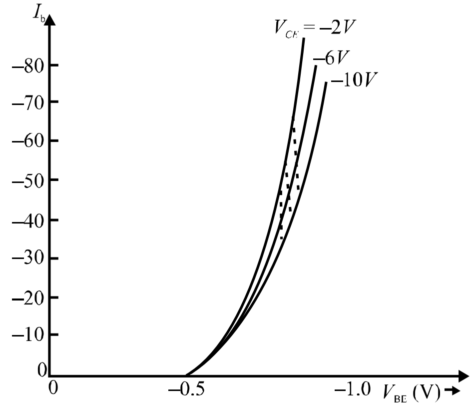


Fig. 28.27 : Input characteristics of a typical *p-n-p* transistor in *CE* configuration.

You may also recall that these curves are similar to the ones obtained for the *CE* configuration for *n-p-n* transistor.

From the reciprocal of the slope of the curve of input characteristic, the a.c input resistance of the transistor can be calculated.

- ***a.c* input resistance (R_{in})** of the transistor in *CE* configuration is expressed as:

$$R_{in} = \left.\frac{\Delta V_{BC}}{\Delta I_B}\right|_{V_{CE}} = \text{constant} \qquad (28.7)$$

In this configuration R_{in} is typically of the order of one $k\Omega$.

Output Characteristics

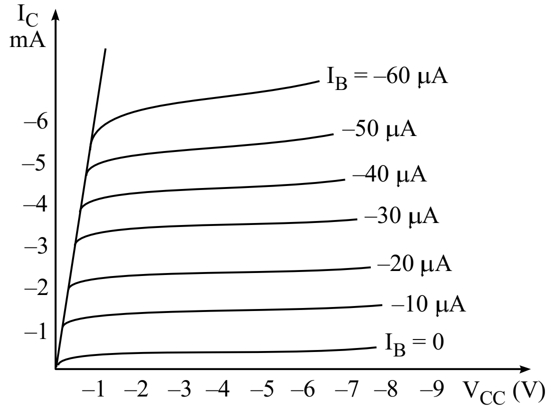


Fig 28.28 : Output characteristics of a typical *pnp* transistor in *CB* configuration

These are graphs between collector-emitter voltage (V_{CE}) and the collector current (I_C) at different constant values of base current (I_B).

To draw these characteristics, V_{CE} is made zero and V_{BE} is adjusted till the microammeter in the base-emitter circuit is set to read a constant value. Thus V_{CE} is adjusted to make I_B constant at a particular value. Now keeping I_B constant, V_{CE} is increased from zero in a number of steps and the corresponding collector current I_C is noted with the help of milliammeter connected in series with collector.

How can we plot the output characteristics at I_B = 50 µA? To do so, V_{BE} is adjusted till milliammeter reads 50 µA. Increase V_{CE} gradually and note correspoding values of I_C. The graph betweent V_{CE} and I_C gives the output characteristics at I_B = 50 µA. Similarly, the output characteristics can be obtained at I_B = 100 µA, 200 µA and so on. Fig. 28.28 shows output characteristics of *p-n-p* transistor for *CE* configuration.

Example 28.1 : Calculate the current gain β of a transistor if the current gain α = 0.98

Solution: $\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$

Example 28.2 : In a transistor, 1 mA change in emitter current changes collector current by 0.99 mA. Determine the a.c current gain.

Solution: Given ΔI_e = 1 mA = 1×10^{-3} A and ΔI_c = 0.99 mA = 0.99×10^{-3} A

Therefore, a.c current gain of the transistor $\alpha = \frac{\Delta I_c}{\Delta I_e} = \frac{0.99\times10^{-3}}{1\times10^{-3}\,A}$ A = 0.99

INTEXT QUESTIONS 28.7

1. Fill in the blanks

   (a) The .... curve relates the input current with input voltage, for a given output voltage.

(b) The .... curve relates the output current with the output voltage for a given input current.

(c) In common emitter configuration of a transistor, the .... and .... are the output terminals

(d) The .... and .... are the input terminals, whereas .... and .... are the output terminals of a transistor in common base configuration.

WHAT YOU HAVE LEARNT

- Semiconductors are materials like silicon (Si) and germanium (Ge), which have conductivities midway between insulators and conductors.
- Semiconductors are of two types : Intrinsic (pure) and extrinsic (dopped).
- Extrinsic semiconductors can be *p*-type (dopped with 3rd group impurities) or *n*-type (doped with 5^{th} group impurities).
- A *p-n* junction diode consists of a *n*-type region and a *p*-type region, with terminals on each end.
- When a *p-n* junction is formed, diffusion of holes and electrons across the junction results in a depletion region which has no mobile charges.
- The ions in the region adjacent to the depletion region generate a potential difference across the junction.
- A forward biased *p-n* junction offers low resistance to flow of electrons.
- A reverse biased *p-n* junction diode offers high resistance to flow of current.
- A *p-n* junction allows current to flow in only one direction.
- There are various types of diode e.g. photo diode light emitting diode, Zener diode and solar cell.
- A photo diode is always connected in reverse bias.
- A transistor consists of three separate regions (emitter, base and collector) and two junctions. Emitter is most heavily doped and base is the least doped. While collector has the largest size, base is the thinnest.
- Transistor can either be *n-p-n* type or *p-n-p* type.
- A transistor can be connected in any of the three configurations: common collector (*CE*), common base (*CB*) or common emitter (*CE*).
- The characteristics of a transistor vary according to the configuration of the transistor.
- *CE* configuration is preferred over other configurations as it provides high current gain and voltage gain.

ANSWERS TO INTEXT QUESTIONS

28.1

1. 1.5×10^{15} each 2. (ii)
3. impurity, doping 4. majority 5. lower

28.2

1. (a) majority carriers (b) depletion region
   (c) 0.7, 0.3 (d) higher, electrons
2. (a) (iii), (b) (iii), (c) (ii)

28.3

3. (a) decreases (b) increases (c) increases, breakdown voltage
4. (a) (iv); (b) (iii)

28.4

2. (a) 0.7 V, 0.3 V; (b) one (c) micro ampere
3. (a) (iii) ; (b) (ii)

28.5

1. (ii), (i), (iv)
2. (a) Zener (b) reverse (c) light sensitive
   (d) group III-V (e) forward (f) emission
   (g) recombination (h) electroluminiscence
   (i) photovoltaic (j) more, absorbed
3. Separation of electrons and holes takes palce due to the electric field of the depletion layer.

28.6

1. (a) (i); (b) (ii)
2. (a) Three, two; (b) Base (c) Most heavily, base
   (d) largest size, moderate (e) Emitter-base, collector-base
   (f) *npn, pnp*

28.7

1. (a) input characteristic (b) output characteristics
   (c) collector, emitter (d) base and emitter, base and collector