Example 14.7 Why are Si and GaAs are preferred materials for solar cells?

Solution The solar radiation spectrum received by us is shown in Fig. 14.26.

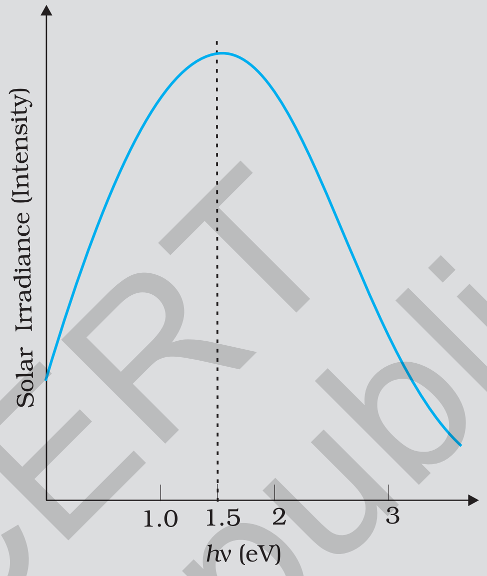


FIGURE 14.26

The maxima is near 1.5 eV. For photo-excitation, $h\nu > E_g$. Hence, semiconductor with band gap ~1.5 eV or lower is likely to give better solar conversion efficiency. Silicon has $E_g \sim 1.1$ eV while for GaAs it is ~1.53 eV. In fact, GaAs is better (in spite of its higher band gap) than Si because of its relatively higher absorption coefficient. If we choose materials like CdS or CdSe ($E_g \sim 2.4$ eV), we can use only the high energy component of the solar energy for photo-conversion and a significant part of energy will be of no use.

The question arises: why we do not use material like PbS ($E_g \sim 0.4$ eV) which satisfy the condition $h\nu > E_g$ for ν maxima corresponding to the solar radiation spectra? If we do so, most of the solar radiation will be absorbed on the *top-layer* of solar cell and will not reach in or near the depletion region. For effective electron-hole separation, due to the junction field, we want the photo-generation to occur in the junction region only.

EXAMPLE 14.7

14.9 JUNCTION TRANSISTOR

The credit of inventing the transistor in the year 1947 goes to J. Bardeen and W.H. Brattain of Bell Telephone Laboratories, U.S.A. That transistor was a point-contact transistor. The first junction transistor consisting of two back-to-back p-n junctions was invented by William Schockley in 1951.

As long as only the junction transistor was known, it was known simply as transistor. But over the years new types of transistors were invented and to differentiate it from the new ones it is now called the Bipolar Junction Transistor (BJT). Even now, often the word transistor is used to mean BJT when there is no confusion. Since our study is limited to only BJT, we shall use the word transistor for BJT without any ambiguity.

14.9.1 Transistor: structure and action

A transistor has three doped regions forming two p-n junctions between them. Obviously, there are two types of transistors, as shown in Fig. 14.27.

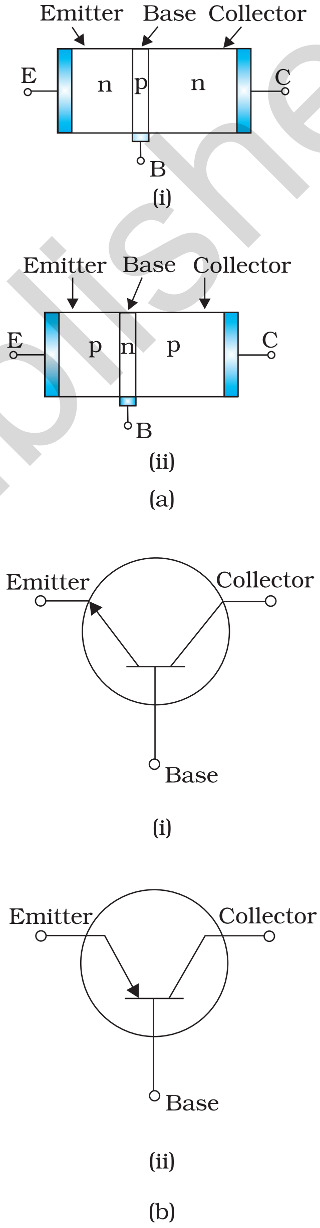


FIGURE 14.27 (a) Schematic representations of a n-p-n transistor and p-n-p transistor, and (b) Symbols for n-p-n and p-n-p transistors.

(i) n-p-n transistor: Here two segments of n-type semiconductor (emitter and collector) are separated by a segment of p-type semiconductor (base).

(ii) p-n-p transistor: Here two segments of p-type semiconductor (termed as emitter and collector) are separated by a segment of n-type semiconductor (termed as base).

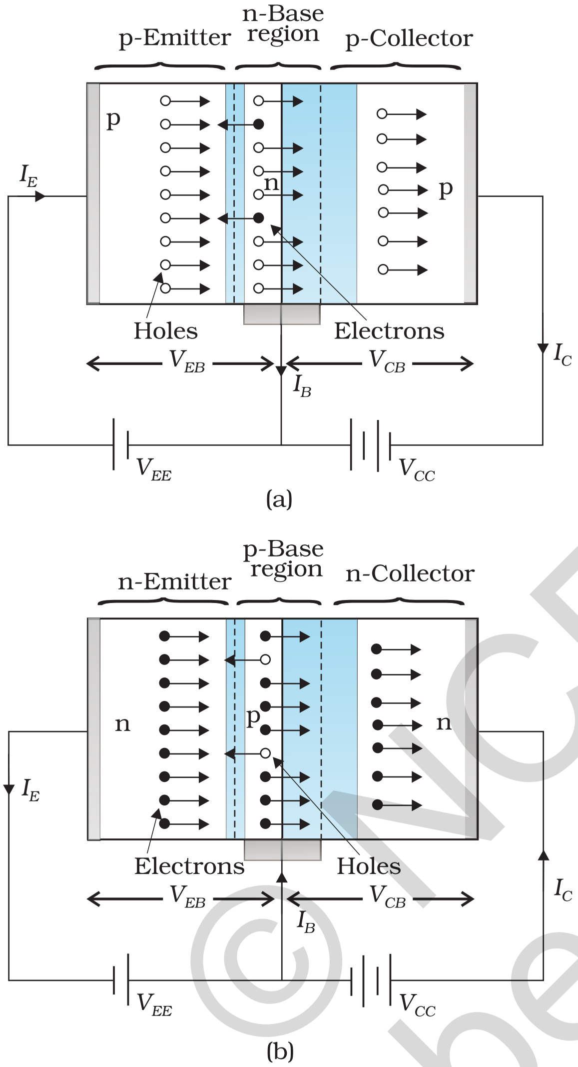
The schematic representations of an n-p-n and a p-n-p configuration are shown in Fig. 14.27(a). All the three segments of a transistor have different thickness and their doping levels are also different. In the schematic symbols used for representing p-n-p and n-p-n transistors [Fig. 14.27(b)] the arrowhead shows the direction of conventional current in the transistor. A brief description of the three segments of a transistor is given below:

- *Emitter*: This is the segment on one side of the transistor shown in Fig. 14.27(a). It is of *moderate size* and *heavily doped*. It supplies a large number of majority carriers for the current flow through the transistor.
- *Base*: This is the central segment. *It is very thin* and *lightly doped*.
- *Collector*: This segment collects a *major* portion of the majority carriers supplied by the emitter. The collector side is *moderately doped* and *larger* in size as compared to the *emitter*.

We have seen earlier in the case of a p-n junction, that there is a formation of depletion region acorss the junction. In case of a transistor depletion regions are formed at the emitter base-junction and the base-collector junction. For understanding the action of a transistor, we have to consider the nature of depletion regions formed at these junctions. The charge carriers move across different regions of the transistor when proper voltages are applied across its terminals.

The biasing of the transistor is done differently for different uses. The transistor can be used in two distinct ways. Basically, it was invented to function as an amplifier, a device which produces a enlarged copy of a signal. But later its use as a switch acquired equal importance. We shall study both these functions and the ways the transistor is biased to achieve these mutually exclusive functions.

First we shall see what gives the transistor its amplifying capabilities. The transistor works as an amplifier, with its emitter -base junction forward biased and the base-collector junction reverse biased. This situation is shown in Fig. 14.28, where V_{CC} and V_{EE} are used for creating the respective biasing. When the transistor is biased in this way it is said to be in *active* state. We represent the voltage between emitter and base as V_{EB} and that between the collector and the base as V_{CB}. In



(a)

(b)

FIGURE 14.28 Bias Voltage applied on: (a) p-n-p transistor and (b) n-p-n transistor.

Fig. 14.28, base is a common terminal for the two power supplies whose other terminals are connected to emitter and collector, respectively. So the two power supplies are represented as V_{EE}, and V_{CC}, respectively. In circuits, where emitter is the common terminal, the power supply between the base and the emitter is represented as V_{BB} and that between collector and emitter as V_{CC}.

Let us see now the paths of current carriers in the transistor with emitter-base junction forward biased and base-collector junction reverse biased. The heavily doped emitter has a high concentration of majority carriers, which will be holes in a p-n-p transistor and electrons in an n-p-n transistor. These majority carriers enter the base region in large numbers. The base is thin and lightly doped. So the majority carriers there would be few. In a p-n-p transistor the majority carriers in the base are electrons since base is of n-type semiconductor. The large number of holes entering the base from the emitter swamps the small number of electrons there. As the base collector-junction is reverse-biased, these holes, which appear as minority carriers at the junction, can easily cross the junction and enter the collector. The holes in the base could move either towards the base terminal to combine with the electrons entering from outside or cross the junction to enter into the collector and reach the collector terminal. The base is made thin so that most of the holes find themselves near the reverse-biased base-collector junction and so cross the junction instead of moving to the base terminal.

It is interesting to note that due to forward bias a large current enters the emitter-base junction, but most of it is diverted to adjacent reverse-biased base-collector junction and the current coming out of the base becomes a very small fraction of the current that entered the junction. If we represent the hole current and the electron current crossing the forward biased junction by I_h and I_e respectively then the total current in a forward biased diode is the sum $I_h + I_e$. We see that the emitter current $I_E = I_h + I_e$ but the base current $I_B << I_h + I_e$, because a major part of I_E goes to collector instead of coming out of the base terminal. The base current is thus a small fraction of the emitter current.

The current entering into the emitter from outside is equal to the emitter current I_E. Similarly the current emerging from the base terminal is I_B and that from collector terminal is I_C. It is obvious from the above description and also from a straight forward application of Kirchhoff's law to Fig. 14.28(a) that the emitter current is the sum of collector current and base current:

$$I_E = I_C + I_B \tag{14.7}$$

We also see that $I_C \approx I_E$.

Our description of the direction of motion of the holes is identical with the direction of the conventional current. But the direction of motion of electrons is just opposite to that of the current. Thus in a p-n-p transistor the current enters from emitter into base whereas in a n-p-n transistor it enters from the base into the emitter. The arrowhead in the emitter shows the direction of the conventional current.

The description about the paths followed by the majority and minority carriers in a n-p-n is exactly the same as that for the p-n-p transistor. But the current paths are exactly opposite, as shown in Fig. 14.28. In Fig. 14.28(b) the electrons are the majority carriers supplied by the n-type emitter region. They cross the thin p-base region and are able to reach the collector to give the collector current, I_C . From the above description we can conclude that in the active state of the transistor the emitter-base junction acts as a low resistance while the base collector acts as a high resistance.

14.9.2 Basic transistor circuit configurations and transistor characteristics

In a transistor, only three terminals are available, viz., *Emitter* (E), *Base* (B) and *Collector* (C). Therefore, in a circuit the input/output connections have to be such that one of these (E, B or C) is common to both the input and the output. Accordingly, the transistor can be *connected* in either of the following three configurations:

Common Emitter (CE), Common Base (CB), Common Collector (CC)

The transistor is most widely used in the CE configuration and we shall restrict our discussion to only this configuration. Since more commonly used transistors are n-p-n Si transistors, we shall confine our discussion to such transistors only. With p-n-p transistors the polarities of the external power supplies are to be inverted.

Common emitter transistor characteristics

When a transistor is used in CE configuration, the input is between the base and the emitter and the output is between the collector and the emitter. The variation of the base current I_B with the base-emitter voltage V_{BE} is called the *input characteristic*. Similarly, the variation of the collector current I_C with the collector-emitter voltage V_{CE} is called the *output characteristic*. You will see that the output characteristics are controlled by the input characteristics. This implies that the collector current changes with the base current.

The input and the output characteristics of an n-p-n transistors can be studied by using the circuit shown in Fig. 14.29.

To study the input characteristics of the transistor in C_E configuration, a curve is plotted between the base current I_B against the base-emitter voltage V_{BE}. The

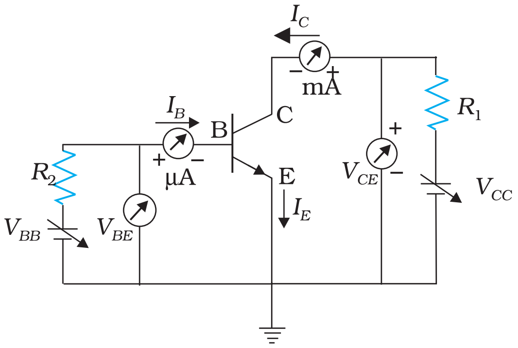


FIGURE 14.29 Circuit arrangement for studying the input and output characteristics of n-p-n transistor in CE configuration.

collector-emitter voltage V_{CE} is kept fixed while studying the dependence of I_B on V_{BE}. We are interested to obtain the input characteristic when the transistor is in active state. So the collector-emitter voltage V_{CE} is kept large enough to make the base collector junction reverse biased. Since $V_{CE} = V_{CB} + V_{BE}$ and for Si transistor V_{BE} is 0.6 to 0.7 V, V_{CE} must be sufficiently larger than 0.7 V. Since the transistor is operated as an amplifier over large range of V_{CE}, the reverse bias across the base-collector junction is high most of the time. Therefore, the input characteristics may be obtained for V_{CE} somewhere in the range of 3 V to 20 V. Since *the increase in* V_{CE} *appears as increase in* V_{CB}, *its effect on* I_B *is negligible*. As a consequence, input characteristics for various values of V_{CE} will give almost identical curves. Hence, *it is enough to determine only one input characteristics*. The input characteristics of a transistor is as shown in Fig. 14.30(a).

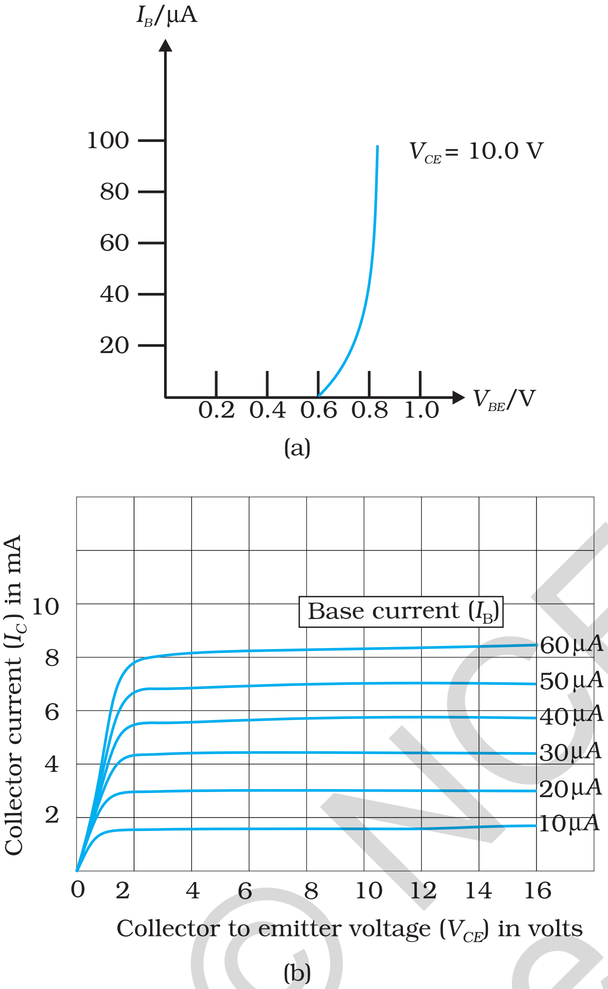


FIGURE 14.30 (a) Typical input characteristics, and (b) Typical output characteristics.

The output characteristic is obtained by observing the variation of I_C as V_{CE} is varied keeping I_B constant. It is obvious that if V_{BE} is increased by a small amount, both hole current from the emitter region and the electron current from the base region will increase. As a consequence both I_B and I_C will increase proportionately. This shows that when I_B increases I_C also increases. The plot of I_C versus V_{CE} for different fixed values of I_B gives one output characteristic. So there will be different output characteristics corresponding to different values of I_B as shown in Fig. 14.30(b).

The linear segments of both the input and output characteristics can be used to calculate some important ac parameters of transistors as shown below.

(i) ***Input resistance*** **(r_i):** This is defined as the ratio of change in base-emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) at constant collector-emitter voltage (V_{CE}). This is dynamic (ac resistance) and as can be seen from the input characteristic, its value varies with the operating current in the transistor:

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}} \qquad (14.8)$$

The value of r_i can be anything from a few hundreds to a few thousand ohms.

(ii) *Output resistance* (r_o): This is defined as the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at a constant base current I_B.

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B} \tag{14.9}$$

The output characteristics show that initially for very small values of V_{CE}, I_C increases almost linearly. This happens because the base-collector junction is not reverse biased and the transistor is not in active state. In fact, the transistor is in the saturation state and the current is controlled by the supply voltage V_{CC} (=V_{CE}) in this part of the characteristic. When V_{CE} is more than that required to reverse bias the base-collector junction, I_C increases very little with V_{CE}. The reciprocal of the slope of the linear part of the output characteristic gives the values of *ro*. The output resistance of the transistor is mainly controlled by the bias of the base-collector junction. The high magnitude of the output resistance (of the order of 100 kΩ) is due to the reverse-biased state of this diode. This also explains why the resistance at the initial part of the characteristic, when the transistor is in saturation state, is very low.

(iii) *Current amplification factor* (β): This is defined as the ratio of the change in collector current to the change in base current at a constant collector-emitter voltage (V_{CE}) when the transistor is in active state.

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}} \tag{14.10}$$

This is also known as *small signal current gain* and its value is very large.

If we simply find the ratio of I_C and I_B we get what is called dc β of the transistor. Hence,

$$\beta_{dc} = \frac{I_C}{I_B} \tag{14.11}$$

Since I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal. So, for most calculations β_{dc} can be used. Both β_{ac} and β_{dc} vary with V_{CE} and I_B (or I_C) slightly.

Example 14.8 From the output characteristics shown in Fig. 14.30(b), calculate the values of β_{ac} and β_{dc} of the transistor when V_{CE} is 10 V and I_C = 4.0 mA.

Solution

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}, \quad \beta_{dc} = \frac{I_C}{I_B}$$

For determining β_{ac} and β_{dc} at the stated values of V_{CE} and I_C one can proceed as follows. Consider any two characteristics for two values of I_B which lie above and below the given value of I_C. Here I_C = 4.0 mA. (Choose characteristics for I_B= 30 and 20 μA.) At V_{CE} = 10 V we read the two values of I_C from the graph. Then

EXAMPLE 14.8

Example 14.8

ΔI_B = (30 – 20) μA = 10 μA, ΔI_C = (4.5 – 3.0) mA = 1.5 mA

Therefore, β_{ac} = 1.5 mA/ 10 μA = 150

For determining $\beta_{dc,}$ either estimate the value of I_B corresponding to I_C = 4.0 mA at V_{CE} = 10 V or calculate the two values of β_{dc} for the two characteristics chosen and find their mean.

Therefore, for I_C = 4.5 mA and I_B = 30 μA,

β_{dc} = 4.5 mA/ 30 μA = 150

and for I_C = 3.0 mA and I_B = 20 μA

β_{dc} =3.0 mA / 20 μA = 150

Hence, β_{dc} =(150 + 150) /2 = 150

14.9.3 Transistor as a device

The transistor can be used as a device application depending on the configuration used (namely CB, CC and CE), the biasing of the E-B and B-C junction and the operation region namely cutoff, active region and saturation. As mentioned earlier we have confined only to the CE configuration and will be concentrating on the biasing and the operation region to understand the working of a device.

When the transistor is used in the cutoff or saturation state it acts as a *switch*. On the other hand for using the transistor as an *amplifier*, it has to operate in the active region.

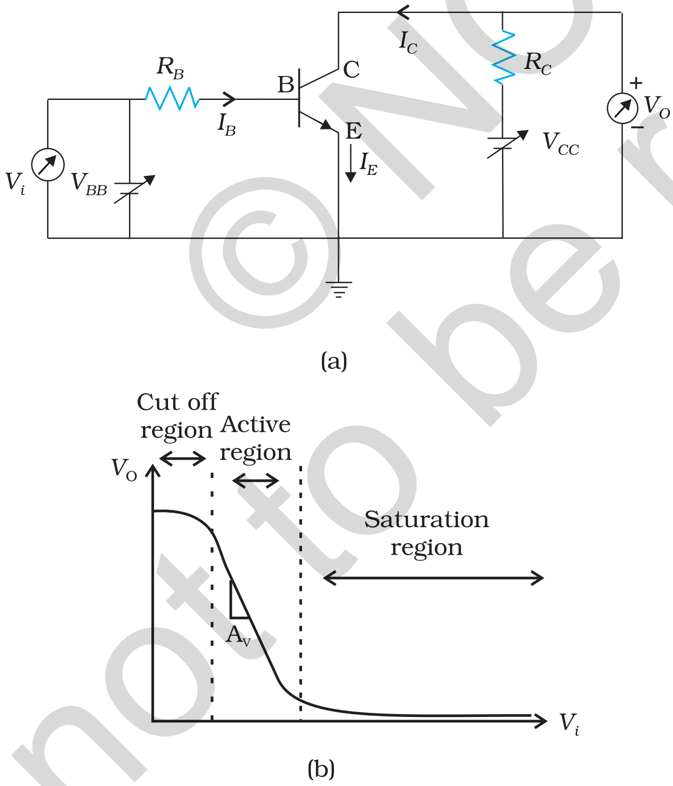


FIGURE 14.31 (a) Base-biased transistor in CE configuration, (b) Transfer characteristic.

(i) Transistor as a switch

We shall try to understand the operation of the transistor as a switch by analysing the behaviour of the base-biased transistor in CE configuration as shown in Fig. 14.31(a).

Applying Kirchhoff's voltage rule to the input and output sides of this circuit, we get

$$V_{BB} = I_B R_B + V_{BE} \qquad (14.12)$$

and

$$V_{CE} = V_{CC} - I_C R_{C.} \qquad (14.13)$$

We shall treat V_{BB} as the dc input voltage V_i and V_{CE} as the dc output voltage V_O. So, we have

$V_i = I_B R_B + V_{BE}$ and

$V_o = V_{CC} - I_C R_C$.

Let us see how V_o changes as V_i increases from zero onwards. In the case of Si transistor, as long as input V_i is less than 0.6 V, the transistor will be in cut off state and current I_C will be zero.

Hence $V_o = V_{CC}$

When V_i becomes greater than 0.6 V the transistor is in active state with some current I_C in the output path and the output V_o decrease as the