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CHAPTER 57

BIPOLAR JUNCTION TRANSISTOR

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Bipolar junction transistor is used in two broad areas-as a linear amplifier to boost or amplify an electrical signal and as an electronic switch

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57.1. Bipolar Junction Transistor

The transistor was invented by a team of three scientists at Bell Laboratories, USA in 1947. Although the first transistor was not a bipolar junction device, yet it was the beginning of a technological revolution that is still continuing in the twenty first century. All of the complex electronic devices and systems developed or in use today, are an outgrowth of early developments in semiconductor transistors.

There are two basic types of transistors : (1) the bipolar junction transistor (BJT) which we will study in this chapter and the field-effect transistor (FET) which is covered in chapter 13. The bipolar junction transistor is used in two broad areas of electronics : (1) as a linear amplifier to boost an electrical signal and (2) as an electronic switch.

Basically, the bipolar junction transistor consists of two back-to-back *P-N* junctions manufactured in a single piece of a semiconductor crystal. These two junctions give rise to three regions called *emitter*, *base* and *collector*. As shown in Fig. 57.1 (*a*) junction transistor is simply a sandwich of one type of semiconductor material between two layers of the other type. Fig. 57.1 (*a*) shows a layer of *N*-type material sandwiched between two layers of *P*-type material. It is described as a *PNP* transistor. Fig. 57.1 (*b*) shown an *NPN* – transistor consisting of a layer of *P*-type material sandwiched between two layers of *N*-type material.

Bipolar junction transistor

The emitter, base and collector are provided with terminals which are labelled as *E*, *B* and *C*. The two junctions are : emitter-base (*E*/*B*) junction and collector-base (*C*/*B*) junction.

The symbols employed for *PNP* and *NPN* transistors are also shown in Fig. 57.1. The arrowhead is always at the emitter (not at the collector) and in each case, its direction indicates the *conventional* direction of current flow. For a *PNP* transistor, arrowhead points from emitter to base meaning that emitter is positive with respect to base (and also with respect to collector)* For *NPN* transistor, it points from base to emitter meaning that base (and collector as well)* is positive with respect to the emitter.

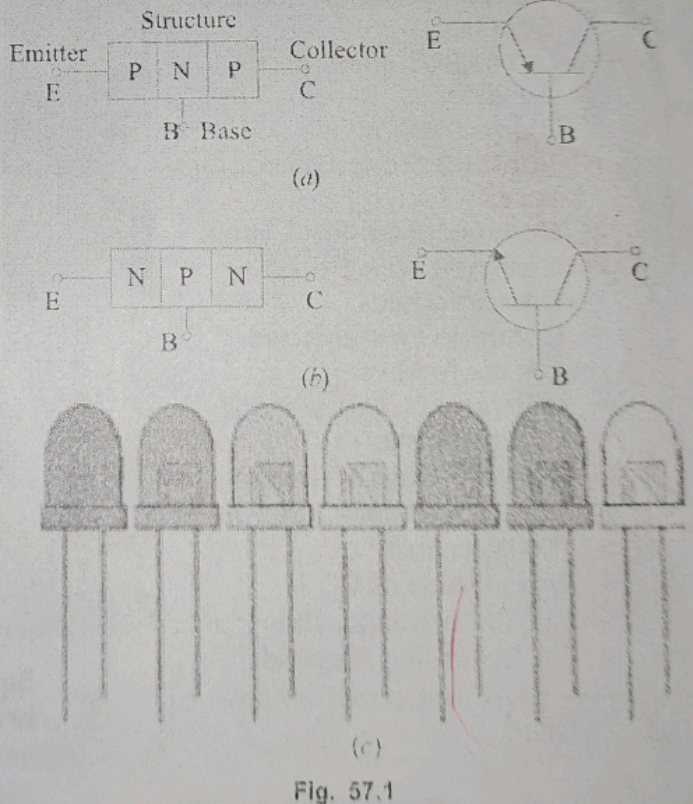

Fig. 57.1

1. Emitter

It is more heavily doped than any of the other regions because its main function is to supply majority charge carries (either electrons or holes) to the base.

2. Base

It forms the middle section of the transistor. It is very thin (10^{-6} m) as compared to either the emitter or collector and is very *lightly-doped*.

3. Collector

Its main function (as indicated by its name) is to collect majority charge carriers coming from the emitter and passing through the base.

* In a transistor, for normal operation, collector and base have the same polarity with respect to the emitter (Art. 57.3)

In most transistors, collector region is made physically larger than the emitter region because it has to dissipate much greater power. Because of this difference, there is no possibility of inverting the transistor *i.e.* making its collector the emitter and its emitter the collector. Fig 57.1 (*c*), shows the picture of C1815 (front and the back view) transistor.

57.2. Transistor Biasing

For proper working of a transistor, it is essential to apply voltages of correct polarity across its two junctions. It is worthwhile to remember that for normal operation;

1. emitter-base junction is always forward-biased and

-ve to +ve 2. collector-base junction is always reverse-biased.

This type of biasing is known as *FR* biasing.

In Fig. 57.2, two batteries respectively provide the dc emitter supply voltage V_{EE} and collector supply voltage V_{CC} for properly biasing the two junctions of the transistor. In Fig. 57.2 (*a*), Positive terminal of V_{EE} is connected to P-type emitter in order to repel or Push holes into the base.

The negative terminal of V_{CC} is connected to the collector so that it may *attract* or *pull* holes through the base. Similar considerations apply to the *NPN* transistor of Fig. 57.2 (*b*). It must be remembered that a transistor will never conduct any current if its emitter-base junction is not forward-biased.* Also refer to the picture shown in Fig. 57.2 (*c*).

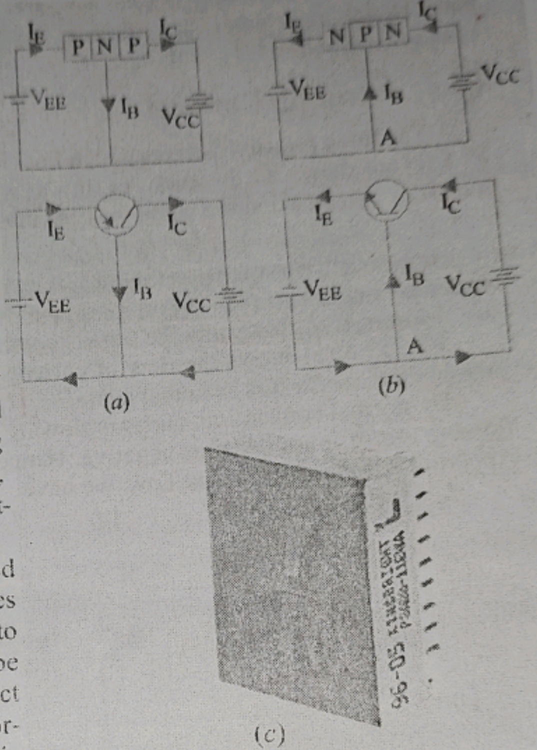

Fig. 57.2

57.3. Important Biasing Rule

For a *PNP* transistor, both collector and base are negative with respect to the emmitter (the letter *N* of Negative being the same as the middle letter of *PNP*). Of course, collector is *more negative* than base [Fig. 57.3 (*a*)]. Similarly, for *NPN* transistor, both collector and base are positive with respect to the emitter (the letter P of Positive being the same as the middle letter of *NPN*). Again, collector is *more positive* than the base as shown in Fig. 57.3 (*b*).

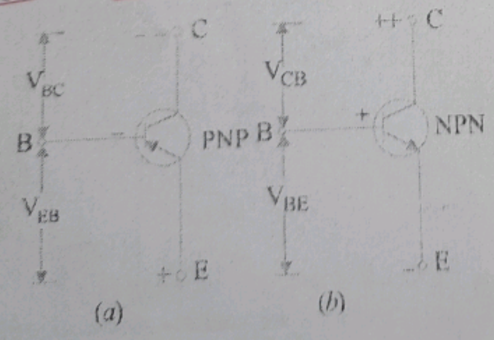

Fig. 57.3

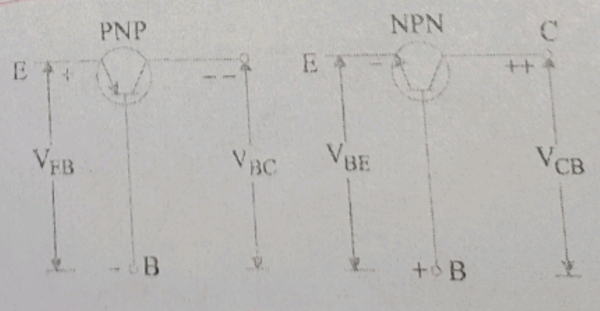

Fig. 57.4

* There would be no current due to majority charge carriers. However, there would be an extremely small current due to minority charge carriers which is called leakage current of the transistor (Art. 57.12).

It may be noted that different potentials have been designated by double subscripts. The first subscript always represents the point or terminal which is more positive (or less negative) than the point or terminal represented by the second subscript. For example, in Fig. 57.3 (*a*), the potential difference between emitter and base is written as V_{EB} (and not V_{BE}) because *emitter is positive with respect to base*. Now, between the base and collector themselves, collector is more negative than base. Hence, their potential difference is written as V_{BC} and not as V_{CB}. Same is the case with voltages marked in Fig. 57.4.

57.4. Transistor Currents

The three primary currents which flow in a properly-biased transistor are I_E, I_B and I_C. In Fig. 57.5 (*a*) are shown the directions of flow as well as relative magnitudes of these currents for a *PNP* transistor connected in the common-base mode. It is seen that again,

$$\boxed{I_E = I_B + I_C}$$

It means that a small part (about 1—2%) of emitter current goes to supply base current and the remaining major part (98—99%) goes to supply collector current.

Moreover, I_E flows into the transistor whereas both I_B and I_C flow out of it.

Fig. 57.5 (*b*) shows the flow of currents in the same transistor when connected in the common-emitter mode. It is seen that again, $\boxed{I_E = I_B + I_C}$

By normal convention, currents flowing *into* a transistor are taken as positive whereas those flowing *out* of it are taken as negative. Hence, I_E is positive whereas both I_B and I_C are negative. Applying Kirchhoff's Current Law, we have

$$I_E + (-I_B) + (-I_C) = 0 \quad \text{or} \quad I_E - I_B - I_C = 0 \quad \text{or} \quad I_E = I_B + I_C.$$

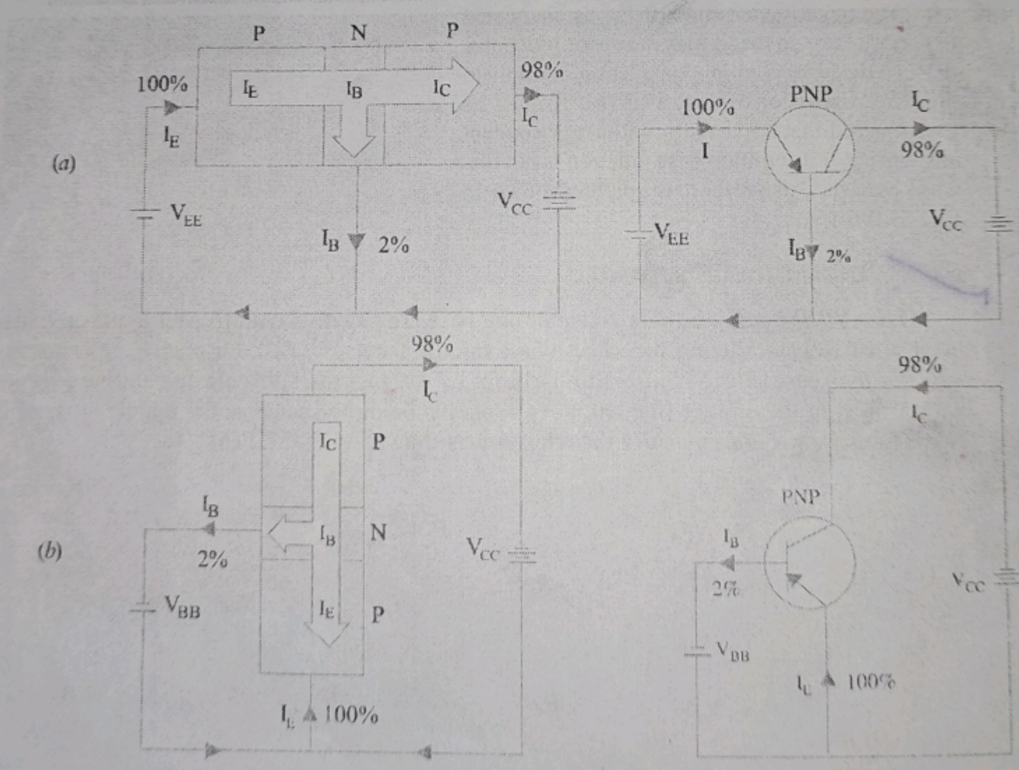

Fig. 57.5

This statement is true *regardless of transistor type or transistor configuration.*

Note. For the time being, we have not taken into account the leakage currents which exist in a transistor (Art. 57.12).

57.5. Summing Up

The four basic guideposts about all transistor circuits are :

1. conventional current flows along the arrow whereas electrons flow against it;
2. E/B junction is always forward-biased;
3. C/B junction is always reverse-biased;
4. $I_E = I_B + I_C$.

57.6. Transistor Circuit Configurations

Basically, there are three types of circuit connections (called configurations) for operating a transistor.

1. common-base (*CB*), 2. common-emitter (*CE*), 3. common-collector (*CC*).

The term 'common' is used to denote the electrode that is common to the input and output circuits. Because the common electrode is generally grounded, these modes of operation are frequently referred to as grounded-base, grounded-emitter and grounded-collector configurations as shown in Fig. 57.6 for a *PNP* – transistor.

Since a transistor is a 3-terminal (and not a 4-terminal) device, one of its terminals has to be common to the input and output circuits.

57.7. CB Configuration

In this configuration, emitter current I_E is the input current and collector current I_C is the output current. The input signal is applied between the emitter and base whereas output is taken out from the collector and base as shown in Fig. 57.6 (*a*).

The ratio of the collector current to the emitter current is called dc alpha (α_{dc}) of a transistor.

$$\therefore \quad \alpha_{dc}{}^{*} = \frac{-I_C}{I_E}$$

The negative sign is due to the fact that current I_E flows into the transistor whereas I_C flows out of it. Hence, I_E is taken as positive and I_C as negative.

$$\therefore \quad I_C = -\alpha_{dc} . I_E$$

If we write αdc simply as α**, then $\alpha = I_E / I_C$

It is also called forward current transfer ratio ($-h_{FB}$). In h_{FB}, subscript *F* stands for forward and *B* for common-base. The subscript d.c. on a signifies that this ratio is defined from dc values of I_C and I_E.

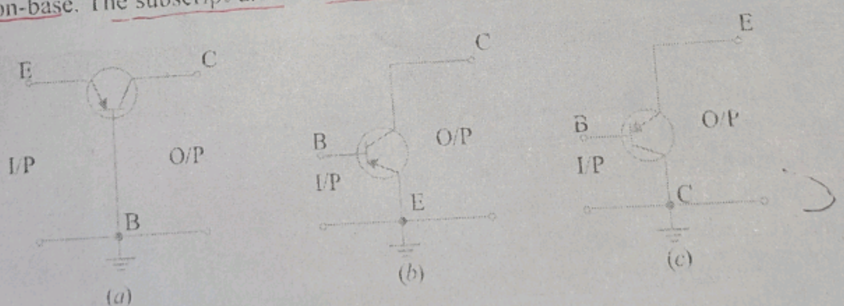

Fig. 57.6

The α of a tranistor is a measure of the quality of a transistor : higher the value of α, better the transistor in the sense that collector current more closely equals the emitter current. Its value ranges

* More accurately, $\alpha_{dc} = \dfrac{I_C - I_{CBO}}{I_E}$ ...Art.57.12

** Negative sign has been omitted, since we are here concerned with only magnitudes of the currents involved.

from 0.95 to 0.999. Obviously, it applies only to *CB* configuration of a transistor. As seen from above and Fig. 57.7. $I_E = I_B + I_C \Rightarrow I_B = I_E - I_C$

$I_C = \alpha I_E$ Now, $I_B = I_E - \alpha I_E = (1 - \alpha) I_E$

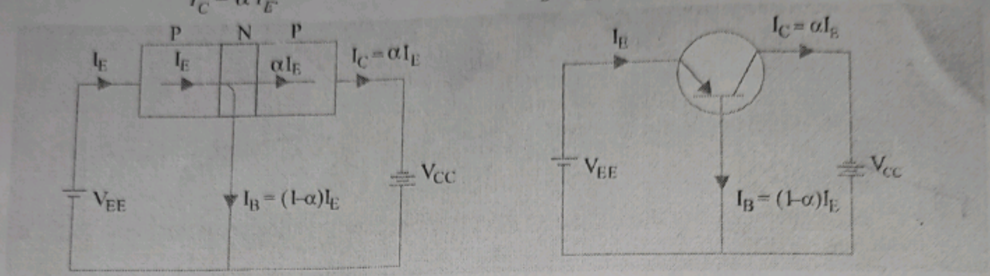

Fig. 57.7

Incidentally, there is also an a.c. α for a transistor. It refers to the ratio of *change* in collector current to the *change* in emitter current.

$$\therefore \qquad \alpha_{ac} = \frac{-\Delta I_C}{\Delta I_E}$$

It is also known as short-circuit gain of a transistor and is written as $-h_{fb}$. It may be noted that upper case subscript '*FB*' indicates dc value whereas lower case subscript '*fb*' indicates ac value. For all practical purposes, $\alpha_{dc} = \alpha_{ac} = \alpha$.

Example 57.1. *Following current readings are obtained in a transistor connected in CB configuration : $I_E = 2$ mA and $I_B = 20$ mA. Compute the values of α and I_C.*

(Electronics-II, Punjab Univ. 1992)

Solution. $I_C = I_E - I_B = 2 \times 10^{-3} - 20 \times 10^{-6} = 1.98$ mA
$\alpha = I_C / I_E = 1.98/2 = 0.99$

57.8. CE Configuration

Here, input signal is applied between the base and emitter and output signal is taken out from the collector and emitter circuit. As seen from Fig. 57.6 (*b*), I_B is the input current and I_C is the output current.

The ratio of the d.c. collector current to dc base current is called dc beta (β_{dc}) or just β of the transistor.

$\therefore \quad \beta = -I_C / -I_B = I_C / I_B$ or $I_C = \beta I_B$ — Fig. 57.8 (*a*)

It is also called common-emitter d.c. *forward transfer ratio* and is written as h_{FE}. It is possible for β to have as high a value as 500.

While analysing ac operation of a transistor, we use ac β which is given by $\beta_{ac} = \Delta I_C / \Delta I_B$.

It is also written as h_{fe}.

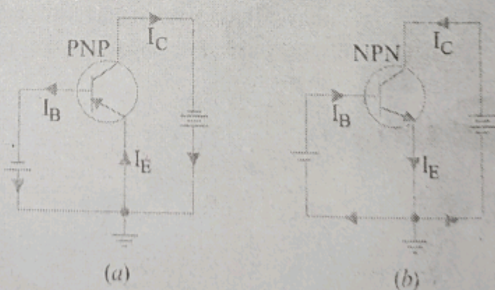

Fig. 57.8

The flow of various currents in a *CE* configuration both for *PNP* and *NPN* transistor is shown in Fig. 57.8. As seen

$$I_E = I_B + I_C = I_B + \beta I_B = (1 + \beta) I_B$$

57.9. Relation Between α and β

$$\beta = \frac{I_C}{I_B} \quad \text{and} \quad \alpha = \frac{I_C}{I_E} \quad \therefore \quad \frac{\beta}{\alpha} = \frac{I_E}{I_B}$$

— only numerical value of α

Now, $I_B = I_E - I_C$ $\quad\therefore\quad$ $\beta = \frac{I_C}{I_E - I_C} = \frac{I_C / I_E}{I_E / I_E - I_C / I_E}$ or $\beta = \frac{\alpha}{1-\alpha}$ – (1)

Cross-multiplying the above equation and simplifying it, we get

$\beta(1-a) = \alpha$ or $\beta = \alpha(1+\beta)$ or $\alpha = \beta/(1+\beta)$ → (2)

It is seen from the about 2 equations that $1 - \alpha = 1/(1+\beta)$

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

From eqn (1)
$1-\alpha = \frac{\alpha}{\beta}$
By putting the value of β
$1-\alpha = \frac{\cancel{\beta}}{(1+\beta)} \times \cancel{\beta}$
$\boxed{1-\alpha = \frac{1}{(1+\beta)}}$

57.10. CC Configuration

In this case, input signal is applied between base and collector and output signal is taken out from emitter-collector circuit [Fig. 57.6 (c)]. Conventionally speaking, here I_B is the input current and I_E is the output current as shown in Fig. 57.9. The current gain of the circuit is

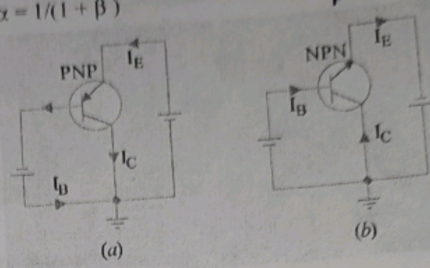

Fig. 57.9

$$\frac{I_E}{I_B} = \frac{I_E}{I_C} \cdot \frac{I_C}{I_B} = \frac{\beta}{\alpha} = \frac{\beta}{\beta/(1+\beta)} = (1+\beta)$$

The flow paths of various currents in a *CC* configuration are shown in Fig. 57.9. It is seen that

$\beta = \frac{I_C}{I_B}$

$I_E = I_B + I_C = I_B + \beta I_B = (1+\beta) I_B$

$\therefore$ output current $= (1+\beta) \times$ input current.

$I_C = \beta I_B$

57.11. Relations Between Transistor Currents

While deriving various equations, following definitions should be kept in mind.

$$\alpha = \frac{I_C}{I_E}, \qquad \beta = \frac{I_C}{I_B}, \qquad \alpha = \frac{\beta}{(1+\beta)} \text{ and } \beta = \frac{\alpha}{(1-\alpha)}$$

(*i*) $I_C = \beta I_B = \alpha I_E = \frac{\beta}{1+\beta} I_E$ $\qquad$ (*ii*) $I_B = \frac{I_C}{\beta} = \frac{I_E}{1+\beta} = (1-\alpha) I_E$

(*iii*) $I_E = \frac{I_C}{\alpha} = \frac{1+\beta}{\beta} I_C = (1+\beta) I_B = \frac{I_B}{(1-\alpha)}$

(*iv*) The three transistor d.c. currents always bear the following ratio*

$I_E : I_B : I_C \quad :: \quad 1 : (1-\alpha) : \alpha$

Incidentally, it may be noted that for ac currents, small letters i_e, i_b and i_c are used.

57.12. Leakage Currents in a Transistor

(*a*) CB Circuit

Consider the *CB* transistor circuit shown in Fig. 57.11. The emitter current (due to majority carriers) initiated by the forward-biased emitter base junction is split into two parts :

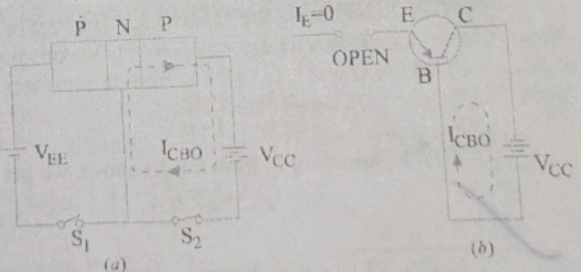

Fig. 57.10

(*i*) $(1-\alpha) I_E$ which becomes base current I_B in the external circuit and

(*ii*) αI_E which becomes collector current I_C in the external circuit.

* It reminds us of the power distribution relationship in an induction motor.

As mentioned earlier (Art. 57.2), though C/B junction is reverse-biased for majority charge carriers (*i.e.* holes in this case), it is forward-biased so far as thermally-generated minority charge carriers (*i.e.* electrons in this case) are concerned. This current flows even when emitter is disconnected from its dc supply as shown in Fig. 57.10 (*a*) where switch, S_1 is open. It flows in the *same* direction* as the collector current of majority carriers. It is called leakage current I_{CBO}. The subscripts CBO stand for 'Collector to Base with emitter Open.' Very often, it is simply written as I_{CO}.

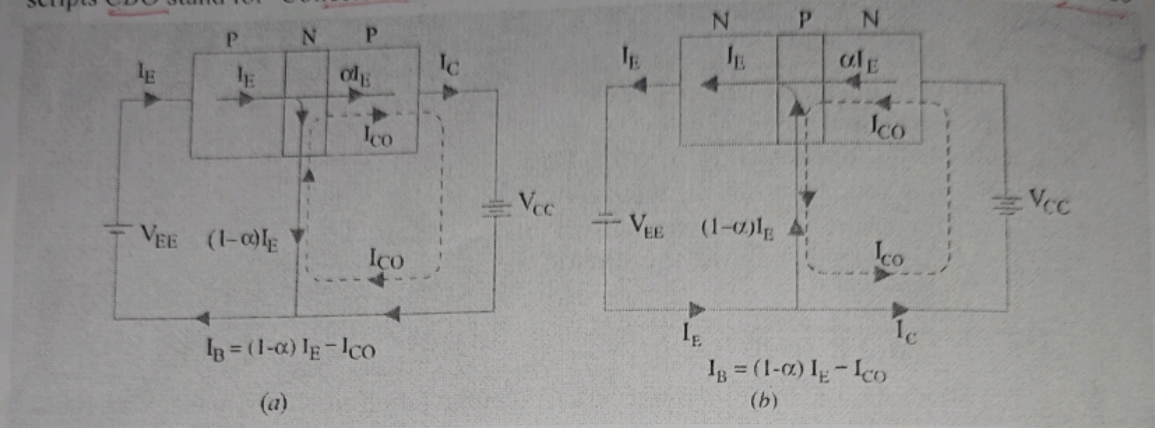

Fig. 57.11

It should be noted that

(*i*) I_{CBO} is exactly like the reverse saturation current I_S or I_0 of a reverse-biased diode discussed in Art. 57.1.

(*ii*) I_{CBO} is extremely temperature-dependent because it is made up of thermally-generated minority carriers. As mentioned earlier, I_{CBO} doubles for every 10°C rise in temperature for *Ge* and 6°C for *Si*.

If we take into account the leakage current, the current distribution in a *CB* transistor circuit becomes as shown in Fig. 57.11 both for *PNP* and *NPN* type transistors.

It is seen that total collector current is actually the sum of two components :

(*i*) current produced by normal transistor action *i.e.* component controlled by emitter current. Its value is αI_E and is due to majority carriers.

(*ii*) temperature-dependent leakage current I_{CO} due to minority carriers.

$$\therefore \quad I_C = \alpha I_E + I_{CO} \quad \ldots(i) \quad \therefore \quad \alpha = \frac{I_C - I_{CO}}{I_E}$$

Since $I_{CO} \ll I_C$, hence $\alpha \cong I_C / I_E$

(*iii*) Substituting the value of $I_E = (I_C + I_B)$ in Eq. (*i*) above, we get

$$I_C = (I_C + I_B) + I_{CO} \quad \text{or} \quad I_C(1-\alpha) = \alpha I_B + I_{CO}$$

$$\therefore \quad I_C = \frac{\alpha I_B}{1-\alpha} + \frac{I_{CO}}{1-\alpha}$$

(*iv*) Eliminating I_C from Eq. (i) above, we get

$$(I_E - I_B) = \alpha I_E + I_{CO} \quad \text{or} \quad I_B = (1-\alpha)\,I_E - I_{CO}$$

(*b*) CE Circuit

In Fig. 57.12 (*a*) is shown a common-emitter circuit of an *NPN* transistor whose base lead is

* Actually, electrons (which form minority charge carriers in collector) flow from negative terminal of collector battery, to collector, then to base through C/B junction and finally, to positive terminal of V_{CC}. However, conventional current flows in the opposite direction as shown by dotted lien in Fig. 57.10 (*a*)

57.29. BJT Switches

Very often, bipolar junction transistors are used as electronic switches. With the help of such a switch, a given load can be turned ON or OFF by a small control signal. This control signal might be the one appearing at the output of a digital logic or a microprocessor. The power level of the control signal is usually very small and, hence, it is incapable of switching the load directly. However, such a control signal is certainly capable of providing enough base drive to switch a transistor ON or OFF and, hence, the transistor is made to switch the load.

When using BJT as a switch, usually two levels of control signal are employed. With one level, the transistor operates in the cut-off region (open) whereas with the other level, it operates in the saturation region and acts as a short-circuit. Fig. 57.44 (*b*) shows the condition when control signal $v_i = 0$. In this case, the *BE* junction is reverse-biased and the transistor is open and, hence acts as an open switch. However, as shown in Fig. 57.44 (*c*) if v_i equals a positive voltage of sufficient magnitude to produce saturation *i.e.* if $v_i = v_i$ the transistor acts as a closed switch.

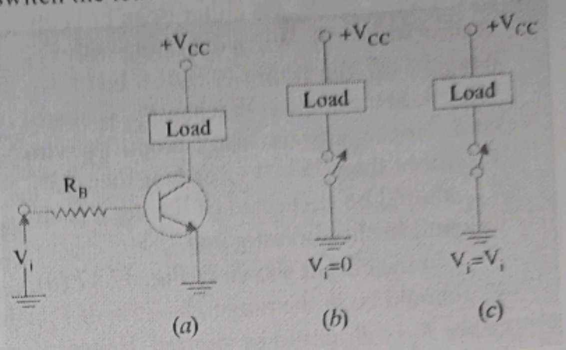

Fig. 57.44

Fig. 57.45 shows a form of series switching circuit utilizing an *NPN* transistor with a negative dc supply and a control signal voltage having levels of zero and $-v_i$.

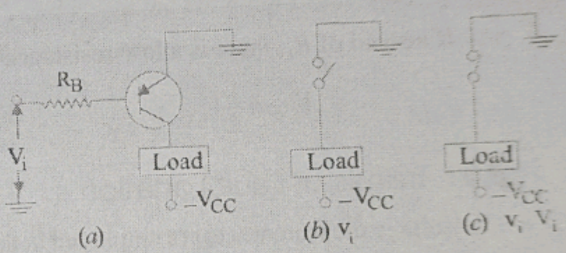

Fig. 57.45

Example 57.20. *The circuit of Fig. 57.46 is designed to produce nearly constant current through the variable collector load resistance. An ideal 6V source is used to establish the current. Determine (a) value of I_C and V_E. (b) range of R_C over which the circuit will function properly. Assume silicon transistor and a b large enough to justify the assumptions used.*

(Applied Electronics-II, Punjab Univ. 1993)

Solution. (*a*) $I_C \cong I_E = (6 - 0.7)/530 = 10$ mA

$V_E = 6 - 530 \times (10 \times 10) = 5.3$ V.

This voltage will remain constant so long as transistor operation is confined to active region.

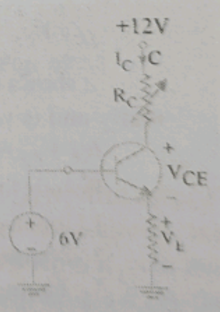

Fig. 57.46

(*b*) When $R_C = 0$

$V_{CE} = 12 - 5.3 = 6.7$ V

It is certainly well within the active region. As R_C increases, its drop increases and hence, V_{CE} decreases. There will be some value of R_C at which active region operation ceases.

Now, $V_{CE} = 12 - 5.3 - I_C R_C = 6.7 - I_C R_C$

Value of $R_{C(max)}$ can be found by puting $V_{CE} = 0$

$\therefore \quad 0 = 6.7 - I_C R_{C(max)}$

or $R_{C(max)} = 6.7/I_C = 6.7/0.01 = 670\ \Omega$

Hence, circuit will function as a constant current source so long as R_C is in the range $0 < R_C <$ 670 Ω. When R_C exceeds 670 Ω, the *BJT* becomes saturated.