University of Calcutta
Semester 4
PHYSICS
Paper: PHS-A-CC-4-10-TH (OLD SYLLABUS)

Transistor: Physical Mechanism of Current Flow, Active Cut off Saturation Region
Solved Problems
Assignments

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To get flow of current in a transistor, the transistor should be biased.

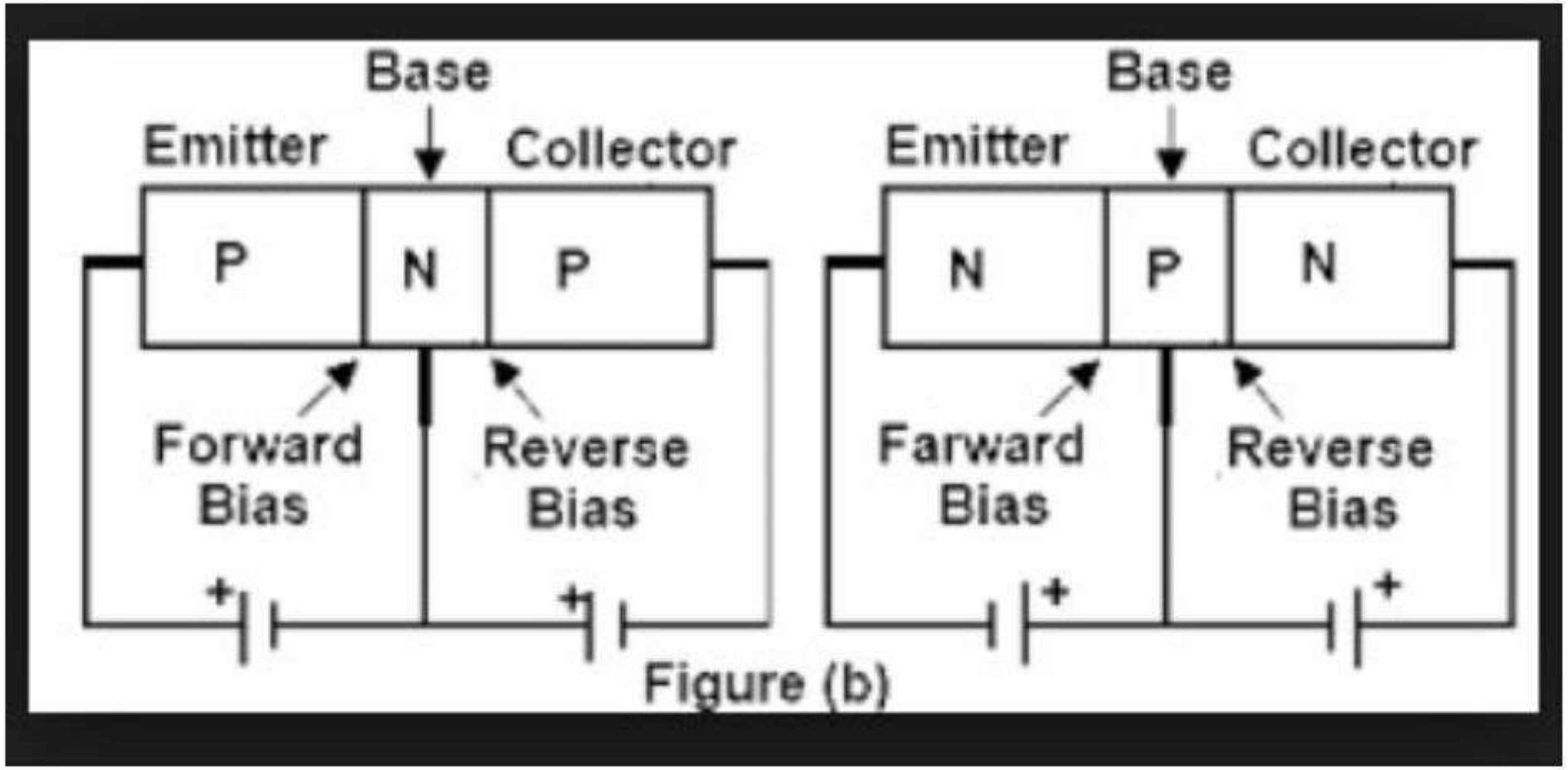
So, understanding of biasing is the basic .

Depending on biasing, the current will flow through the transistor.

Clear your idea and basic concept

https://youtu.be/7ukDKVHnac4

Basic knowledge about biasing of a Transistor



bipolar junction transistor

Seeing this picture, please note that which junction will be given which type of biasing

Physical mechanism of Current flow

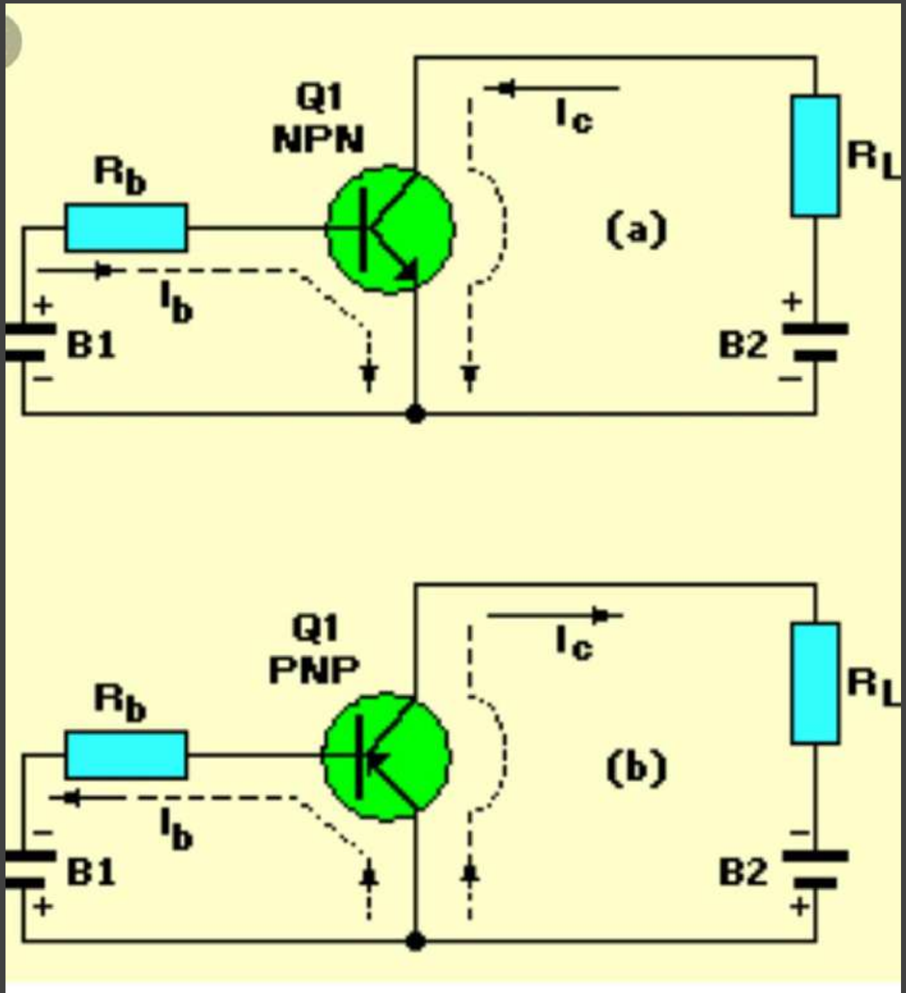
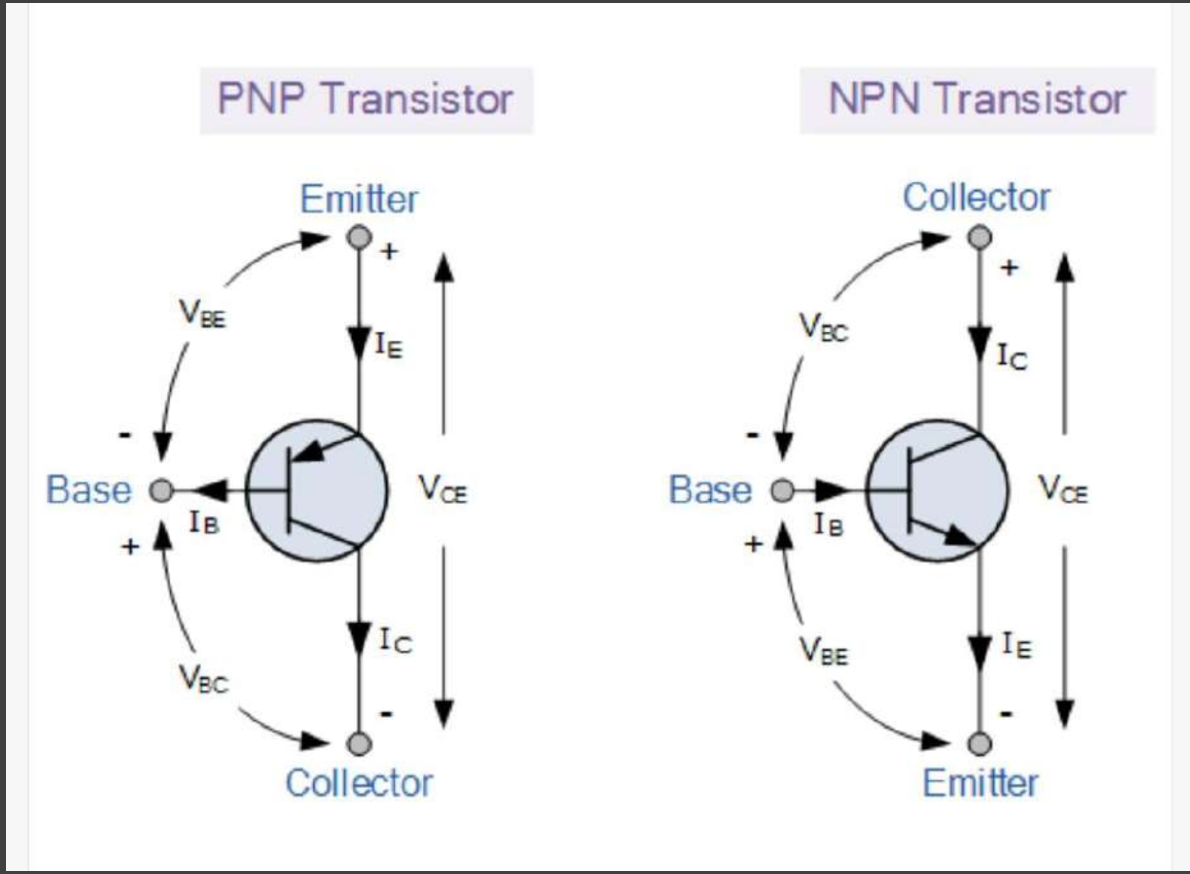


Fig. 3--CURRENT FLOW in transistors:
NPN (a), and PNP (b).



7.5 CURRENT COMPONENTS IN A TRANSISTOR

Figure 7.6 shows the different current components flowing across the forward-biased emitter-base junction (J_E) and the reverse-biased collector-base junction (J_C) of a *p-n-p* transistor. The emitter current I_E is made up of the component $I_E(p)$ due to the holes injected from the emitter into the base and the component $I_E(n)$ due to the electrons crossing from the base into the emitter. Thus

$$I_E = I_E(p) + I_E(n) \tag{7.5}$$

As the emitter doping is much higher than the base doping in a commercial transistor, $I_E(p) >> I_E(n)$, so that the emitter current arises almost entirely from the injected holes. All the currents in Eq. (7.5) are positive for a *p-n-p* transistor.

Most of the holes crossing the emitter junction J_E reach the collector junction J_C producing a hole component $I_{CI}(p)$ of the collector current. The remaining holes recombine with the electrons in the base, giving a recombination hole current $I_E(p) - I_{CI}(p)$, leaving the base.

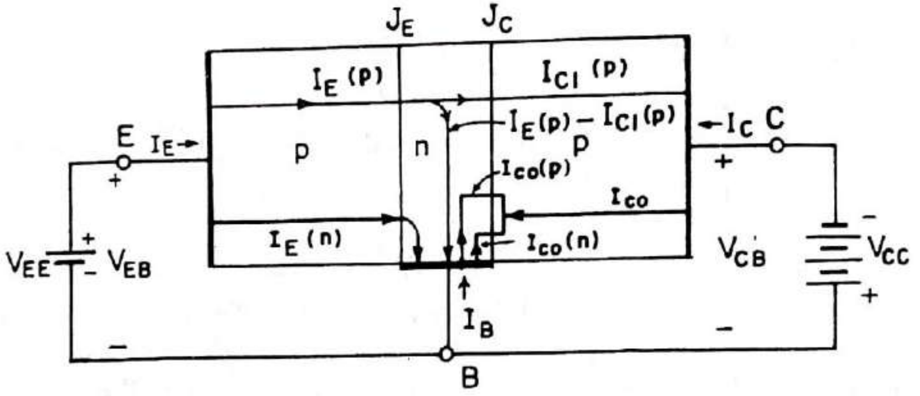


Fig. 7.6 Current components in a *p-n-p* transistor

When the emitter-base junction is open-circuited and the collector-base junction is reverse biased, then $I_E = 0$ and the collector current I_C must be the reverse saturation current I_{CO} of the reverse-based diode at J_C. This reverse current has two components: (i) $I_{CO}(n)$ consisting of the electrons moving from the *p*-side to the *n*-side across J_C, and (ii) $I_{CO}(p)$ due to the holes travelling from the *n*-side to the *p*-side across J_C. With the chosen reference directions in Fig. 7.6, we write

$$-I_{CO} = I_{CO}(n) + I_{CO}(p) \tag{7.6}$$

The total collector current when the emitter is forward-based, is

$$I_C = I_{CO} - I_{CI}(p)\,. \tag{7.7}$$

Usually, I_{CO} is in μA or less and I_C is in mA, so that $I_{CO} << I_{CI}(p)$.

For a *p-n-p* transistor, I_E is positive while both I_C and I_{CO} are negative. This means that the collector current in Fig. 7.6 actually flows in the direction opposite to that indicated by the arrowhead of I_C. For an *n-p-n* transistor, these currents are reversed.

Current component in a transistor

https://youtu.be/Kx5T2nYBJk0

5.6 Static characteristics of a transistor

A bipolar junction transistor is a non-linear device with two *p-n* junctions J_E and J_C which can be biased by different methods. So, a transistor can be operated in different zones depending on the biasing of J_E and J_C, and exact analytical relation between the current and voltage of a transistor cannot be obtained. For this, we have to depend on the experimentally drawn current-voltage characteristic curves, known as *static characteristics* of a transistor. The graphical form of relationship among the different currents and voltages are represented by these characteristics. The characteristics are of *two* types :

(i) Input characteristics—When the input current is plotted against the input voltage with the output voltage as parameter, the curves so obtained are known as *input characteristics*.

(ii) Output characteristics—The plot of output current versus output voltage with the input current as parameter is called *output characteristics*.

The input characteristics and the output characteristics for a transistor in CE and CB mode are very important for practical applications. We are therefore interested in the characteristics of a transistor in CB and CE configurations only.

5.6.1 Common base characteristics

Fig. 5.10 shows the circuit arrangement for studying the static characteristics of a *npn* transistor in CB mode. For a *pnp* transistor, the polarities of the batteries and the meters are to be reversed.

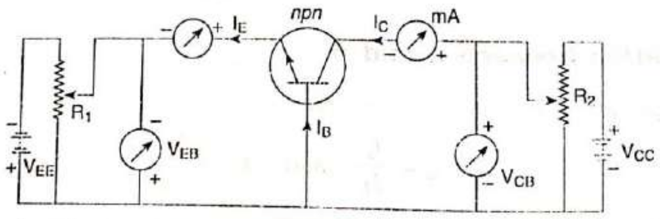


Fig. 5.10 Circuit diagram for characteristics of a *npn* transistor in CB mode

(A) Input characteristics—For the CB configuration of a transistor, the input current and input voltage are the emitter current I_E and the emitter-base voltage V_{EB}. The output voltage is the collector-base voltage V_{CB}. So the input characteristic of CB configuration is the graph between the I_E and V_{EB} with V_{CB} as a parameter. Fig. 5.11 shows the input characteristic curves of a typical *npn* transistor. For normal operation, the emitter-base junction

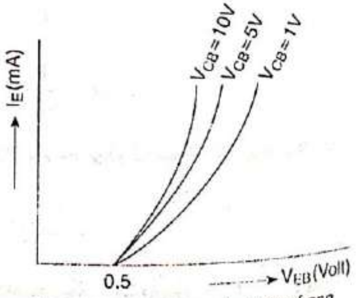


Fig. 5.11 Input characteristics of *npn* Si-transistor in CB mode

is forward biased. So the variation of I_E with V_{EB} is similar to the forward characteristic curve of a *p-n* junction diode with a cut-in voltage V_γ ($\simeq 0.1$ V for Ge and ~ 0.5 V for Si).

An increase in the magnitude of the collector-base voltage causes the width of the depletion region of the collector-base junction to increase. It reduces the effective base width and enhances the gradient of minority carrier resulting in an increase in collector current. The change of the effective base width by the collector-base voltage is called the *early effect* or *base width modulation*.

(B) Output characteristics—For common-base configuration, the collector current I_C and the collector-base voltage V_{CB} are the output current and output voltage respectively. The input current is the emitter current I_E. So, the graph between the collector current I_C versus the collector-base voltage V_{CB} with emitter current I_E as parameter is the CB output characteristic. Fig. 5.12 shows a typical set of output characteristics of a *npn* transistor in CB mode.

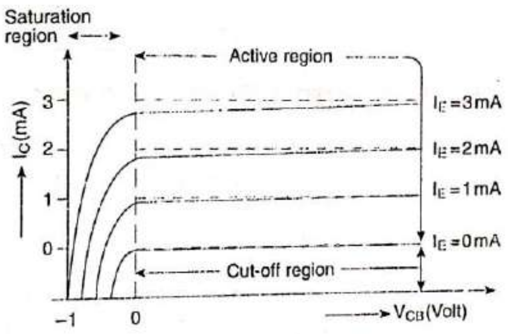


Fig. 5.12 Output characteristics of a *npn* transistor in CB mode

The output characteristics can be divided into *three* distinct regions—*active region, saturation region* and *cut-off region*.

(i) Active region—The normal operating region of a transistor is the active region in which the emitter junction is forward biased and the collector junction is reverse biased. The collector current I_C in CB mode is given by

$$I_C = \alpha I_E + I_{CBO}$$

When the emitter current is zero (at the lower end of the active region), I_C is simply I_{CBO}, the reverse saturation current ($\sim 1\mu$A for Ge and 1 nA for Si). As I_E increases, the collector current becomes $I_C \approx \alpha I_E$ since $I_{CBO} \ll I_E$. As $\alpha \approx 1$, I_C is slightly smaller than I_E. So in the active region, I_C is nearly independent of V_{CB} and depends on I_E. So, the output characteristics are almost parallel lines equally spaced for equal increment in I_E in the active region.

(ii) Saturation region—When both the emitter junction and the collector junction are forward biased, the transistor is operated in the saturation region. This region is located to the left of $V_{CB} = 0$ and above $I_E = 0$ in the output characteristics.

(iii) Cut-off region—The region to the right of $V_{CB} = 0$ and below $I_E = 0$ is the cut-off region. In this region, both the emitter junction and the collector junction are reverse biased.

5.6.2 Common emitter characteristics

The circuit diagram for studying the static characteristics of a *npn* transistor in CE mode is shown in Fig. 5.13. For a *pnp* transistor, the polarities of the batteries and the meters are simply to be reversed.

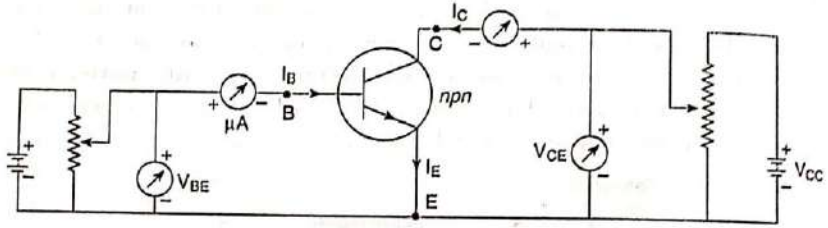


Fig. 5.13 Circuit diagram for CE characteristics of an *npn* transistor

(A) Input characteristics—For CE configuration, base current I_B and emitter-base voltage V_{BE} are the input current and the input voltage respectively and collector-emitter voltage V_{CE} is the output voltage. So, the plot of I_B against V_{BE} with V_{CE} as a parameter represents the CE input characteristics. Fig. 5.14 shows a set of typical CE input characteristics of a *npn* Si-transistor. The input characteristic curves are similar to that of a forward biased *p-n* junction diode.

With increase in magnitude of V_{CE}, the effective base width and hence the recombination base-current is reduced due to early effect. So, for a constant value of V_{BE}, I_B decreases with increase in the magnitude of V_{CE}.

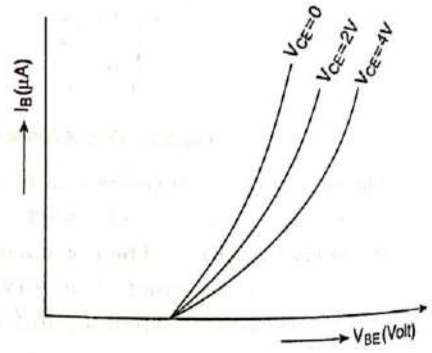


Fig. 5.14 CE input characteristics of an *npn* transistor

(B) Output characteristics—When the output current I_C is plotted against the output voltage V_{CE} taking the input current I_B as parameter, the graph so obtained is called the *output characteristics* for the CE mode. A set of typical CE output characteristics of a *npn* transistor are shown in Fig. 5.15. The output characteristic curves can be divided into *three* regions—*the active region, the cut-off region* and *the saturation region.*

(i) Active region—In this region, the emitter junction is forward biased and the collector junction is reverse biased. In Fig. 5.15, the active region is above $I_B = 0$ and

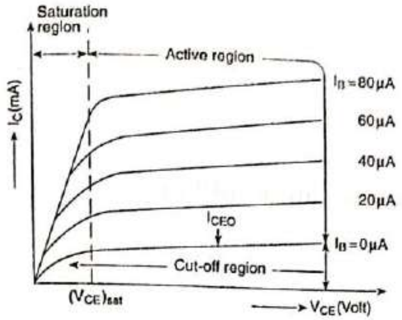


Fig. 5.15 CE output characteristics of a *npn* transistor

to the right of $V_{CE} = (V_{CE})_{sat}$. In this region, the collector current I_C increases with the increase in V_{CE} according to the relation $I_C = \beta I_B + (1+\beta)I_{CBO}$. So, the curves are almost equispaced straight lines having significant upward slope.

(ii) Cut-off region : In CE configuration of a transistor, the collector-current $I_C = (1+\beta)I_{CBO} = I_{CEO}$ with $I_B = 0$. So, the transistor is not cut-off with $I_B = 0$. Since I_{CEO} is the collector to emitter current due to minority carriers with base open, the emitter junction must be reverse biased slightly to cut-off the transistor when $I_B = 0$. For Ge transistor the reverse-bias voltage ~ 0.1 volt and that for Si-transistor 0 volt. The cut-off region is shown in Fig. 5.15 below the curve $I_B = 0$.

(iii) Saturation region—The region where both the emitter junction and the collector junction are forward biased by at least cut-in voltage is called the *saturation region.* The saturation region is very close to the zero voltage axis where all the curves coincide.

5.7 Common collector (CC) connection

When the collector terminal of a transistor is common to both the input and the output circuit, the mode of circuit connection is called the *common collector configuration* or CC *mode.* Fig. 5.16 shows the circuit arrangement of a *npn* transistor in CC mode

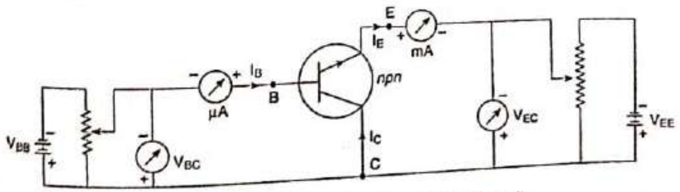


Fig. 5.16 Common collector *npn* transistor circuit

such that the input is applied between the base and the collector while the output is obtained between the emitter and the collector.

Since CC circuit has very high input resistance (~ 750 kΩ) compared to the output resistance (~ 25 Ω), the voltage gain is less than 1 and hence this circuit is not suitable for the purpose of amplification.

Cut off, Active and Saturation Region of a Transistor

https://youtu.be/jTifbBriS-o

https://youtu.be/GIcLxRZkydY

https://youtu.be/GVv2uTgB2sA

Solved problems

1. A Transistor having $\alpha = 0.99$ is used in a common-base amplifier. If the load resistance is 4.5 k Ω and the dynamic resistance of the emitter junction is 50 Ω, find the voltage gain and the power gain.

Ans. The voltage gain is

$$A_v \approx \alpha \frac{R_L}{r_e}$$

Here $\alpha = 0.99$, $R_L = 4.5\ k\ \Omega = 4500\ \Omega$, and $r_e = 50\ \Omega$.

Hence $$A_V = 0.99 \times \frac{4500}{50} = 89.1.$$

The power gain is

$$A_P = \text{current gain} \times \text{voltage gain}$$

$$= 0.99 \times 89.1 = 88.2.$$

2. An *n-p-n* transistor with $\alpha = 0.98$ is operated in the CB configuration. If the emitter current is 3 mA and the reverse saturation current is $I_{CO} = 10\ \mu A$, what are the base current and the collector current?

Ans. The collector current I_C for an emitter current I_E is given by

$\alpha = 0.98$
$I_E = 3\ mA$
$I_{CO} = 10\ \mu A$.

$$I_C = -\alpha I_E + I_{CO}$$

For an *n-p-n* transistor, I_E is negative. Therefore,

$$I_C = \alpha I_E + I_{CO}$$

Since $\alpha = 0.98$, $I_E = 3$ mA, and $I_{CO} = 10\ \mu\ A = 10 \times 10^{-3}$ mA, we have

$$I_C = 0.98 \times 3 + 10^{-2}$$

$$= 2.95\ mA.$$

Also, from Kirchhoff's current law,

$$I_E + I_C + I_B = 0$$

For an *n-p-n* transistor, I_E is negative. Hence

$$-I_E + I_C + I_B = 0$$

or, $$I_B = I_E - I_C = 3 - 2.95 = 0.05\ mA = 50\ \mu A.$$

... reverse saturation current $I_{CO} = 10\ \mu A$ is

4. A transistor is operating in the CE mode (Fig. 7.16). Calculate V_{CE} if $\beta = 125$, assuming $V_{BE} = 0.6$ V.

(cf. C.U. 1991)

Ans. When $V_{BE} = 0.6$ V, the base current is

$$I_B = \frac{10 - V_{BE}}{310\text{k}\,\Omega} = \frac{10 - 0.6}{310}\ \text{mA}$$

$$= 0.0303\ \text{mA}$$

Now, $\beta = 125$. Therefore, $I_C = \beta\, I_B = 125 \times 0.0303$ mA

$$= 3.79\ \text{mA} = 3.79 \times 10^{-3}\ \text{A}.$$

Again $V_{CE} = 20 - I_C \times 5 \times 10^3$ V

$$= 20 - 3.79 \times 5 = 1.05\ \text{V}.$$

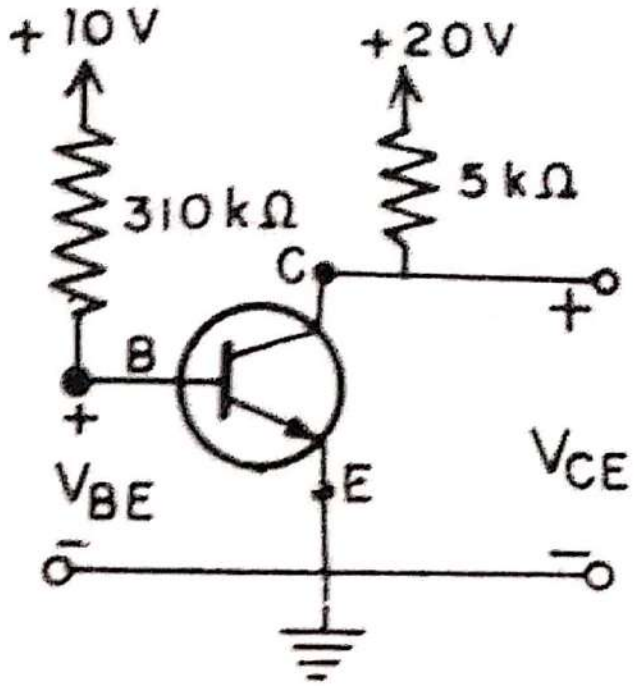


Fig. 7.16. Figure for Problem 4

5. A silicon *n-p-n* transistor having $\beta = 100$ and $I_{C0} = 22\text{nA}$ is operated in the CE configuration (Fig. 7.17). Assuming $V_{BE} = 0.7$ V, determine the transistor

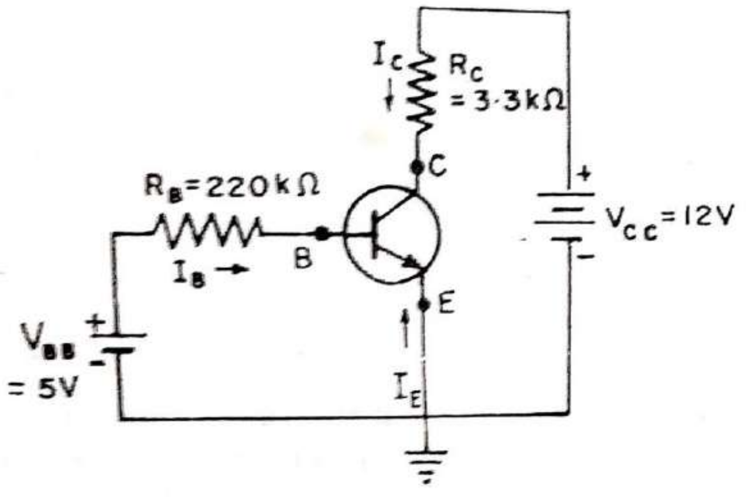


Fig. 7.17 Figure for Problem 5

currents and the region of operation of the transistor. What happens if the resistance R_C is indefinitely increased? (cf. C.U. 1994)

Ans. Since the base is forward-biased, the transistor is not cutoff. So it is either in the active region or in the saturation region.

Let us assume that the transistor is in the active region. Application of Kirchhoff's voltage law to the base circuit gives

$$I_B R_B + V_{BE} = V_{BB}$$

or,
$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{220} \text{ mA} = 0.0195 \text{ mA}$$
$$= 19.5 \ \mu\text{A}.$$

Here $I_{C0} << I_B$. Therefore,

$$I_C \approx \beta I_B = 100 \times 19.5 \times 10^{-3} \text{ mA} = 1.95 \text{ mA}.$$

To justify the assumption that the transistor operates in the active region, we must show that the collector junction is reverse-biased. Applying Kirchhoff's voltage law to the collector circuit, we get

$$I_C R_C + V_{CB} + V_{BE} = V_{CC}$$

or,
$$V_{CB} = V_{CC} - I_C R_C - V_{BE}$$
$$= 12 - 1.95 \times 3.3 - 0.7$$
$$= 4.86 \text{ V}.$$

A positive value of V_{CB} implies that for the *n-p-n* transistor, the collector junction is reverse-biased. Therefore, the transistor is actually in the active region.

The emitter current is

$$I_E = -(I_C + I_B) = -(1.95 + 0.0195) \text{ mA}$$
$$= -1.97 \text{ mA}.$$

The negative sigh indicates that I_E actually flows in the direction opposite to the arrowhead shown in Fig. 7.17.

In the active region, I_B and I_C do not depend on the collector circuit resistance R_C. So, if R_C is gradually increased, we see from the collector circuit equation that at one stage V_{CB} becomes negative. The transistor is then no longer in the active region; it goes over to the saturation region.

Assignment

4. A silicon *n-p-n* transistor with $\alpha = 0.995$ and $I_{C0} = 15$ nA, operates in the CE configuration. What is the collector current for a base current of 20 μA? (**Ans.** 3.983 mA)

5. A *p-n-p* transistor working in the CB mode has an input dynamic resistance of 50Ω. The current gain on the amplifier is 0.98 and the load resistance in the collector circuit is 3 k Ω. Calculate the voltage gain and the power gain. (*cf.* C.U. 1993) (**Ans.** 58.8, 57.6)

9. Consider an *n-p-n* transistor in the CE configuration with negligible I_{C0}. Given: $\beta = 50$, $V_{BB} = 4$V. $R_B = 100$ k Ω, $R_C = 4$ kΩ and $V_{CC} = 10$V. Draw the circuit diagram. Calculate the currents I_B and I_C, assuming $V_{BE} = 0.7$ V in the active region. Find the value of R_C for which the transistor will no longer be in the active region. (C.U. 1991)
(**Ans.** 33μA, 1.65 mA, 5.64 kΩ)

10. Draw the circuit diagram of a common-emitter *n-p-n* transistor with the following parameters: $V_{BB} = 5$ V, $R_B = 100$ kΩ, $R_C = 1$ kΩ, $V_{CC} = 10$ V, $V_{BE} = 0.7$ V, $I_{C0} \approx 0$, and $h_{FE} = 100$. Find I_B and I_C. Is the transistor operating in the saturation region?

(C.U. 1993) (**Ans.** 43 µA, 4.3 mA, No.)

12. In the circuit of Fig. 7.18, $V_{BB} = 3$V, $R_1 = 7$k Ω, $R_E = 500$ Ω, $R_2 = 3$kΩ and $V_{CC} = 10$V. Assume $\beta = h_{FE} = 100$. (i) Determine if the Si transistor is in cutoff, saturation or in the active region. (ii) Calculate the voltage