The collector and base currents of BC107 transistor are 5 mA and 50 μA respectively. If current amplification factor in common base configuration is 98%, calculate the value of collector leakage current in CE and CB configurations.

**Solution:**

\[ \alpha = 0.98, \beta = \frac{\alpha}{1 - \alpha} = 49, \]

\[ I_C = \beta I_B + (1 + \beta) I_{CO} = \beta I_B + I_{CEO} \]
\[ = 49 \times 0.05 \text{ mA} + I_{CEO} = 2.45 \text{ mA} + I_{CEO} \]
\[ I_{CEO} = (5 - 2.45) \text{ mA} = 2.55 \text{ mA} \]
\[ I_{CO} = \frac{I_{CEO}}{1 + \beta} = 0.051 \text{ mA} \]

2. Determine the resulting change in emitter current for a change in the collector current of 2 mA with its \( \alpha = 0.98 \).

**Solution:**

\[ I_C = \alpha I_E + I_{CO} \]
\[ \Delta I_C = \Delta I_E \]
\[ \Delta I_E = \frac{\Delta I_C}{\alpha} = \frac{2 \text{ mA}}{0.98} = 2.04 \text{ mA} \]

3. Obtain \( I_C, \beta, \) and \( I_{CEO} \) in case a BJT having \( I_E = 10 \text{ mA}, I_{CO} = 0.5 \mu\text{A}, \) and \( \alpha = 0.98 \).

**Solution:**

\[ \beta = 49, \]
\[ I_C = \alpha I_E + I_{CO} \]
\[ = (0.98 \times 10 + 0.5 \times 10^{-6}) \text{ mA} = 9.8 \text{ mA} \]
\[ I_{CEO} = (1 + \beta) I_{CO} = 50 \times 0.5 \times 10^{-6} \]
\[ = 25 \mu\text{A} \]

4. If \( I_B \) and \( I_C \) of any BJT are 1mA and 100 mA respectively, determine its current amplification ratio in CB and CE configurations.

**Solution:**

\[ I_E = (1 + \beta) I_B + (1 + \beta) I_{CO} = (1 + \beta) I_B \]
\[ = (1 + 49) \times 1 \text{ mA} = 50 \text{ mA} \]
\[ 1 + \beta = 101 \]
\[ \beta = 100 \]

The current amplification ratio in CE = \( \beta = 100 \)

The current amplification ratio in CB = \( \alpha = \frac{\beta}{1 + \beta} = \frac{100}{101} = 0.990099 = 0.99 \)
5 A \textit{p-n-p} transistor shown in Fig. 5.24 has uniform doping in the emitter, base and collector regions wherein the doping concentrations are $10^{25}/m^3$, $10^{23}/m^3$ and $10^{21}/m^3$ respectively. The minority carrier diffusion length in emitter and the base regions are 5 microns and 100 microns respectively. Assuming low level injection conditions and using law of junction, calculate the collector current density and the base current density due to base recombination. Assume $D_p = 8 \times 10^{-4} m^2/sec$, $D_n = 10 \times 10^{-4} m^2/sec$, $n_i = 1.5 \times 10^{16}/m^3$, $kT/q = 0.026 V$, $q = 1.6 \times 10^{-19} C$.

Solution:

Minority carriers at the entry point of base

$$\text{region} = p_n(o) = p_n \exp \frac{V_{be}}{0.78}$$

$$= p_n \exp 2.25 \times 10^9 \exp^{30}$$

$$= 2.25 \times 10^9 \times 1.069 \times 10^{13}$$

$$= 2.4 \times 10^{22}/m^3$$

Gradient of charge (hole) diffusion

$$= \frac{qD_p p_n(o)}{W_p}$$

$$= \frac{1.6 \times 10^{-19} \times 8 \times 10^{-4} \times 2.4 \times 10^{22}}{5 \times 10^{-6}}$$

$$= 30.72 \times 10^5$$

$$= 6.144 \times 10^5 A/m^2$$

Base current due to recombination

$$= \frac{\text{Excess holes}}{\text{Minority life time } \tau_p}$$

$$\tau_p = \frac{I_B^2}{D_p} = \frac{(100 \times 10^{-6})^2}{8 \times 10^{-4}}$$

$$= 12.5 \times 10^{-6} sec$$

$$I_B = \frac{p_n(o) \times W_p \times q}{2 \tau_p}$$

Figure 5.24

\[
\begin{array}{c|cc|c}
\text{p} & N_A = 10^{25}/m^3 & \text{n} & N_A = 10^{23}/m^3 & \text{p} & N_A = 10^{21}/m^3 \\
L_n = 10 \text{ micron} & & L_n = 100 \text{ micron} & & L_n = 200 \text{ micron} \\
0.78 V \quad 0 \quad 10 V & & & & \\
\end{array}
\]

$$= \frac{2.4 \times 10^{22} \times 5 \times 10^{-6} \times 2 \times 10^{-4}}{2 \times 12.5 \times 10^{-6}}$$

$$= 0.768 \times 10^3 A/m^2$$
6 If the quiescent collector current of an n-p-n transistor for the base-emitter voltage \( V_{BE} = 0.7 \text{ V} \) is \( I_C = 1 \text{ mA} \), what would be the new value of \( V_{BE} \) at \( I_C = 0.1 \text{ mA} \) and \( I_C = 10 \text{ mA} \)?

**Solution:**

\[
I_C = I_S \exp^{V_{BE}/V_T}, \quad 1 = I_S \exp^{0.7/0.026} \\
= I_S \exp^{26.923} = 4.93 \times 10^{11} I_S, \\
I_S = 2 \times 10^{-15} \text{ A,} \\
I_C = I_S \exp^{V_{BE}/V_T} = 2 \times 10^{-15} \exp^{V_{BE}/0.026} \\
= 0.1 \times 10^{-3} \exp^{0.026/0.026} = 0.05 \times 10^{12}, \\
V_{BE} = 0.026 \times 24.6353 = 0.64 \text{ V} \text{ and } V_{BE} = 0.026 \times 29.23 = 0.76 \text{ V} \\
(10 \text{ mA})
\]

7 A BJT has been specified with maximum and minimum value of current amplification factor as \( \beta_{\text{max}} = 150 \) and \( \beta_{\text{min}} = 50 \). Calculate the range of values of \( \alpha \).

**Solution:**

\[
\alpha_{\text{max}} = \frac{\beta}{1 + \beta} = \frac{150}{151} = 0.9934, \quad \alpha_{\text{min}} = \frac{50}{51} \\
= 0.988
\]

8 The base and emitter currents of an n-p-n transistor are 0.0145 mA and 1.45 mA for \( V_{BE} = 0.7 \text{ V} \). Calculate the values of \( \alpha, \beta, \) and \( I_B \).

**Solution:**

\[
I_C = I_E - I_B = (1.45 - 0.0145) \text{ mA} \\
= 1.44 \text{ mA,} \\
\alpha = \frac{I_C}{I_E} = \frac{1.44}{1.45} = 0.99, \\
I_C = \frac{1.44}{0.0145} = 99 \\
I_C = I_S \exp^{V_{BE}/V_T} = I_S \exp^{0.7/0.026} \\
= I_S \exp^{26.923} = I_S \times 4.93 \times 10^{11}, \\
I_S = \frac{1.44 \text{ mA} \times 10^{-11}}{4.93} = 0.293 \times 10^{-11} \\
= 2.93 \times 10^{-15} \text{ A}
\]

9 Calculate the values of current amplification factor \( \beta \) of two different transistors having \( \alpha_1 = 0.99 \) and \( \alpha_2 = 0.98 \) and emitter currents of both being 10 mA. Calculate its base currents also.

**Solution:**

\[
\beta_1 = \frac{\alpha_1}{1 - \alpha_1} = \frac{0.99}{1 - 0.99} = 99, \\
\beta_2 = \frac{\alpha_2}{1 - \alpha_2} = \frac{0.98}{1 - 0.98} = 49, \\
I_{B1} = \frac{10}{1 + 99} = 0.1 \text{ mA}, \\
I_{B2} = \frac{10}{1 + 49} = 0.2 \text{ mA}
\]
10 Calculate the value of the base-emitter voltage ($V_{BE}$) for an $N$-$P$-$N$ transistor having $\beta = 100$, $I_C = 1\text{mA}$, and $I_S = 10^{-11}\text{A}$.

**Solution:**

\[
1.5 \text{mA} = 10^{-11} \exp \frac{V_{BE}}{0.026},
\]

\[
\exp \frac{V_{BE}}{0.026} = 1.5 \times 10^8,
\]

\[
V_{BE} = 0.026 \ln 1.5 \times 10^8
\]

\[
= 0.026 \times 18.826 = 0.5 \text{ V}
\]

11 The BJT in the circuit of Fig. 5.25 has maximum $I_{CO} = 2 \mu\text{A}$ and current amplification factor $\beta_{\text{min}} = 50$, and $\beta_{\text{max}} = 150$. Obtain the value of resistor that can prevent collector voltage falling below 8 V.

**Solution:**

The maximum leakage current $I_{CEO} = (1 + \beta)I_{CD} = 151 \times 2 \mu\text{A} = 302 \mu\text{A}$

\[
R_C I_C = 12 - V_{CE} = 12 - 8 = 4 \text{ V},
\]

\[
R_C = \frac{4000}{302} = 13.3 \text{ K}\Omega
\]

![Figure 5.25](image)

12 What is the minimum base current required so that the transistor shown in Fig. 5.26 enters the saturation region. The transistor parameters at room temperature are $\alpha = 0.98$, $I_{CO} = 2 \mu\text{A}$, $I_{EO} = 1.6 \mu\text{A}$.

**Solution:**

When emitter-base junction is forward biased in the CE configuration, the collector-emitter junction is reverse biased for active region. For saturation to occur the collector-emitter junction is also forward biased i.e. $V_{CE} = 0$.

\[
V_{BE} = V_{CE} = 0, \quad V_{CC} = R_C I_C + V_{CE},
\]

\[
\beta = \frac{0.98}{1 - 0.98} = 49
\]

\[
I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{12}{4 \text{ K}} = 3 \text{ mA},
\]

\[
I_B = \frac{I_C}{\beta} = \frac{3}{49} = 0.0612244 \text{ mA}
\]

As $I_{EO} = 1.6 \mu\text{A} < I_C = 3 \text{ mA}$.

Strictly, $I_C - I_{EO} = \beta I_B, I_B = \frac{I_C - I_{EO}}{\beta}$

\[
= \frac{3 - 0.0016}{49} = 0.061191 \text{ mA}
\]
13 An n\textsuperscript{+}p\textsuperscript{n} transistor having base width $W_B = 2 \times 10^{-4}$ cm, and an emitter area $A_e = 10^{-5}$ cm$^2$ is connected in the circuit of Fig. 5.27. The electrons in the base region have lifetime $\tau_n = 10^{-7}$ sec and diffusion constant $D_n = 36$ cm$^2$/sec. Assume that the transistor characteristics are completely controlled by the parameters of the base region in which low-level condition prevails and that the base to emitter voltage is approximately 0.7 V. Calculate the base current $I_B$ determining the electron concentration $n_{eo}$ in the base at the emitter side of the junction.

**Solution:**

$$I_E = \frac{5.7 - 0.7}{5 K} = 1 \text{ mA}$$

$$I_E = \frac{qAD_B}{L_n} \Delta n_E \cot h(W_B / L_n)$$

$$= \frac{qAD_B}{L_n} \Delta n_E \frac{L_n}{W_B}$$

$$\Delta n_E = \frac{W_n I_E}{qAD_B} = \frac{2 \times 10^{-4} \times 10^{-3}}{1.6 \times 10^{-19} \times 10^{-8} \times 36}$$

$$= 0.035 \times 10^{17} = 3.5 \times 10^{15}/\text{cm}^3$$

$$\tau_n = \frac{I_{Em} - I_{Eo}}{I_{Em} + I_{Eo}} = 1 - \frac{D_n p_{en} W_B}{D_n n_{eo} W_B}$$

$$I_B = \frac{qAD_n}{L_n} \Delta n_B \tanh(W_B / 2L_n)$$

$$= \frac{qAD_n}{L_n} \Delta n_E \frac{W_B}{2L_n} = \frac{qAD_n}{D_n \tau_n} \frac{W_B}{2}$$

$$= \frac{qAD_B}{2 \tau_n} \Delta n_E$$

$$= \frac{1.6 \times 10^{-19} \times 10^{-8} \times 2 \times 10^{-4} \times 3.5 \times 10^{15}}{2 \times 10^{-7}}$$

$$= 5.6 \times 10^{-6} \text{A}$$
The parameters of a typical N-P-N transistor shown in Fig. 5.28 are $W_C = 20 \ \mu m$, collector doping $= 5 \times 10^{18} / cm^3$, $W_E = 1 \ \mu m$, emitter doping $= 10^{19} / cm^3$, base doping $5 \times 10^{15} / cm^3$, and minority carrier lifetime in the base region is $\tau_n = 0.5 \ \mu s$. Under punch through the $V_{BC} = 10 \ \text{V} + \phi_o$ volts. Here $\phi_o$ is the built-in voltage of base-collector junction. The emitter injection efficiency can be assumed as 1 for this transistor. Obtain the base width $W_B$ and the current amplification factor. Given $D_n 30 \ \text{cm}^2 / \text{sec}$, $\varepsilon_S \varepsilon_0 = 10^{-12} F/m$, $n_i = 1.5 \times 10^{10} / cm^3$.

**Solution:**

$$\phi_o = \frac{kT}{q} \ln \frac{N_i N_{iB}}{n_i^2}$$

$$= 0.025 \ln \frac{5 \times 10^{15} \times 5 \times 10^{18}}{1.5^2 \times 10^{20}}$$

$$= 0.025 \ln \frac{25 \times 10^{13}}{225}$$

$$= 0.025 (2.4 + 13 \times 2.3)$$

$$= 0.025 (2.4 + 29.93) = 0.025 (32.33)$$

$$= 0.81 \ \text{V}$$

**Figure 5.28**

10.81 V = \[7.67 \times 10^{-16} N_C W^2\]

\[7.67 \times 10^{-16} \times 5 \times 10^{13} W^2, \quad W = \frac{10.81}{3835}\]

= 2.819, \quad W = 1.68 \mu m

Current amplification factor $\alpha = \frac{I_C}{I_E}$

$$\frac{qA D_n n_{iB} Cosech W_B}{L_n} \frac{W_B}{L_n} = \frac{Cosech W_B}{Cot W_B} \frac{L_n}{L_n}$$

Cosec $hx = \frac{1}{x^2 - 6x + 6 - \frac{x^2}{6x}}$

Cot $hx = \frac{1}{x^2 + 3x + 3 + \frac{x^2}{3x}}$

$L_n = \sqrt{D_n \tau_n} = \sqrt{30 \times 0.5 \times 10^{-6}}$

= $\sqrt{15 \times 10^{-6}} = 3.873 \times 10^{-3} \ \text{cm}$

$$\alpha = \frac{I_C}{I_E} = \frac{Cosech \frac{W_B}{L_n}}{Cot \frac{W_B}{L_n}} = \frac{(6 - x^2)}{6x} \frac{x}{(3 + x^2)} / 3x$$
Punch through voltage = $V_{PT} = 10 + 0.81 = 10.81 \text{ V} = 7.67 \times 10^{-16} \text{ NC}^2 \text{W}^2$

Here, $N_C$ = concentration of lighter region $5 \times 10^{15}/\text{cm}^3 < 5 \times 10^{18}/\text{cm}^3$

$$V_{PT} = \frac{6 - x^2}{(3 + x^3)^2} = \frac{6L_n^2 - W_n^2}{(3L_n^2 + W_n^2)^2}$$

$$= 6 \times 15 \times 10^{-9} - 2.82 \times 10^{-12}$$

$$2(3 \times 15 \times 10^{-9} + 2.82 \times 10^{-12})$$

$$= 89.99$$

15. The BJT used in the circuit of Fig. 5.29 has $I_{CBO} = 2 \mu\text{A}$ at room temperature i.e. $25^\circ\text{C}$ and doubles every $10^\circ\text{C}$ rise in the temperature. What is the maximum value of allowable $R_B$ to keep the BJT in cut-off state at $75^\circ\text{C}$? Given $V_{BE(CUT\_OFF)} = -0.1 \text{ V}$.

**Solution:**

The leakage current at $75^\circ\text{C}$ = $2 \mu\text{A} \times 2^5 = 64 \mu\text{A}$

$$5 \text{ V} + V_{BE} = R_B I_{CBO} = 64 \mu\text{A} R_B$$

or,

$$R_B = \frac{(5 - 0.1) \times 10^9}{64} = 76.7 \text{ K}\Omega$$

**Figure 5.29**

16. What will be the maximum temperature in Problem 15 to bring the BJT out of cut-off region, if the $V_{BE}$ is set to 1 V with $R_B = 50 \text{ K}\Omega$?

**Solution:**

$$1 \text{ V} + V_{BE} = R_B I_{CBO} = 50 K I_{CBO}.$$ $I_{CBO} = \frac{1 \text{ V} - 0.1}{50 \text{ K}} = 0.9 \text{ V} = 0.018 \mu\text{A}.$

$$18 = 2 \times 2^{(15 - 25/10)}, 2^{(15 - 25/10)} = 9,$$

$$\frac{t - 25}{10} = \log_2 9 = 3.2, t = 32 + 25 = 57^\circ\text{C}$$

17. Show that if very small per unit change in $\alpha$ is given as $\alpha$, then the corresponding per unit change in $\beta$ is expressed as $\frac{\Delta \alpha}{\beta} = (1 + \beta) \frac{\Delta \alpha}{\alpha}$.

**Solution:**

$$\alpha = \frac{\beta}{1 + \beta}, \partial \alpha = \frac{\partial \beta (1 + \beta) - \beta \partial \beta}{(1 + \beta)^2}$$

$$= \frac{\partial \beta}{(1 + \beta)^2} \frac{\partial \alpha}{\alpha} = \frac{\partial \beta (1 + \beta)}{(1 + \beta)^2 \beta}$$

$$= \frac{\partial \beta}{(1 + \beta)^2} \frac{\partial \beta}{\beta} = (1 + \beta) \frac{\partial \alpha}{\alpha}.$$
18. If $\alpha$ changes by 0.1%, what would be the value of $\frac{\partial \beta}{\beta}$ for $\beta = 100$?

**Solution:**

$$\frac{\partial \beta}{\beta} = 100 \times 0.1\% = 10.1\%$$

19. What would be the value of leakage current of a transistor at 75°C, if the leakage current is $I_{CEO} = 15$ nA at 25°C?

**Solution:**

$$I_{COH} = I_{CO} \exp^{K_a},$$

$$I_{COE} = I_{CO} \exp^{K_a},$$

$$\frac{I_{COE}}{I_{COH}} = \exp^{K_a (qT_E + qT_C)},$$

$$I_{COE} = I_{COH} \exp^{K_a (qT_E + qT_C)}$$

$$I_{COE} = 15 \text{nA} \exp^{0.07250}$$

$$= 15 \text{nA} \exp^{3.5} = 15 \times 10^{-9} \times 33.12$$

$$= 0.5 \times 10^{-6} \text{ A}$$

20. Accidentally the emitter and collector leads of an npn transistor have been connected in the inverse mode. The resulting emitter and base currents from this configuration are 5 mA and 1 mA. What would be the value of $\alpha_R$ and $\beta^2_R$?

**Solution:**

$$p_R = \frac{I_C}{I_B} = 5, \quad \alpha_R = \frac{I_C}{I_E} = \frac{5}{5+1} = 0.833$$

21. An npn transistor has $V_{BE} = 0.8 \text{ V}$ and collector current of 1 A. What would be the value of $V_{BE}$ for $I_C = 10 \text{ mA}$ and 5 A?

**Solution:**

$$I_C = I_S \exp^{V_{BE}/V_T} = 1 \text{ A}$$

$$= I_S \exp^{0.8/0.026} = I_S \exp^{30.76923}$$

$$= 2.3 \times 10^{13} I_S, \quad I_S = 4.34 \times 10^{-14} \text{ A}$$

$$10 \text{ mA} = 4.34 \times 10^{-14} \exp^{V_{BE}/0.026}$$

$$\exp^{V_{BE}/0.026} = 23 \times 10^{11}$$

$$V_{BE} = 0.026 \times 26.16 = 0.68 \text{ V}$$

$$\exp^{V_{BE}/0.026} = \frac{5 \times 10^{14}}{4.34} = 1.152 \times 10^{14},$$

$$V_{BE} = 0.026 \ln(1.152 \times 10^{14})$$

$$= 0.026 \times 32.38 = 0.842 \text{ V}$$
22 The collector current of a BJT is 12 mA for \( V_{BE} = 0.7 \) V. What would be the collector current if \( V_{BE} \) is reduced to 0.5 V?

**Solution:**

\[
I_C = I_S \exp \frac{V_{BE}}{V_T} = 12 \text{ mA} = I_S \exp^{0.7/0.026}
\]

\[
I_S = \frac{12 \times 10^{-3}}{4.93} = 2.44 \times 10^{-14} \text{ A},
\]

\[
I_C = 2.44 \times 10^{-14} \exp^{0.5/0.026}
\]

\[
= 2.44 \times 10^{-14} \exp^{9.21}
\]

\[
= 2.44 \times 10^{-14} \times 2.25 \times 10^6
\]

\[
= 5.48 \times 10^{-6} \text{ A}
\]

23 What would be the output resistance at collector current of 1 mA of a BJT having Early voltage of 200 V?

**Solution:**

\[
r_o = \frac{V_A}{I_C} = \frac{200}{1 \text{ mA}} = 200 \text{ K} \Omega.
\]

24 For a p-n-p transistor with \( I_s = 10^{-14} \) A and \( \beta = 100 \), calculate \( I_C, I_B, \) and \( I_E \) for \( V_{BE} = 0.7 \) V and \( V_{CE} \leq 0 \).

**Solution:**

\[
I_C = I_s \exp \frac{V_{BE}}{V_T} = 10^{-14} \exp^{0.7/0.026}
\]

\[
= 10^{-14} \exp^{26.93}
\]

\[
= 10^{-14} \times 4.93 \times 10^{11} = 4.93 \times 10^{-3} \text{ A}
\]

\[
I_B = \frac{4.93 \times 10^{-3} \text{ A}}{100} = 0.0493 \times 10^{-3} \text{ A}
\]
The area of emitter-base junction of an n-p-n transistor is 10 μm × 5 μm with the doping concentration in the emitter $N_D = 10^{19}$/cm$^3$, in the base $N_A = 10^{17}$/cm$^3$, in the collector $N_D = 10^{15}$/cm$^3$, $n_i = 1.5 \times 10^{10}$/cm$^3$ at 300 K. The diffusing electrons in the base has $D_n = 21.3$ cm$^2$/s and $L_n = 19 \times 10^{-4}$ cm. For holes diffusing in the emitter has $D_p = 1.7$ cm$^2$/s and $L_p = 0.6 \times 10^{-3}$ cm. Calculate $I_s$ and $\beta$ for base width (a) 1 μm and (b) 5 μm.

**Solution:**

\[
I_s = \frac{qD_n A_p n_i^2}{N_A W} = \frac{1.6 \times 10^{-19} \times 21.3 \times 50 \times 10^{-8} \times 2.25 \times 10^{-20}}{10^{17} \times W} = \frac{1.6 \times 21.3 \times 50 \times 2.25 \times 10^{-7} \times W^{-1}}{10^{17} \times W} = \frac{1.6 \times 21.3 \times 50 \times 2.25 \times 10^{-24} \times W}{W} = 3834 \times 10^{-24} \times \frac{W}{W} = 3834 \times 10^{-24} \times \frac{W}{10^{-4}} = 3.834 \times 10^{-17} \text{A.}
\]

\[
I_s (W = 1 \mu m) = 3.834 \times 10^{-17} \text{A.}
\]

\[
I_s (W = 5 \mu m) = \frac{3834 \times 10^{-24}}{5 \times 10^{-4}} = 0.7668 \times 10^{-17} \text{A.}
\]

\[
\beta = \frac{1}{D_n \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_n}} = \frac{1}{D_p \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{L_n}} = \frac{1}{1.7 \times 10^{17} \times W \times 10^4 + \frac{1}{2} \frac{W^2}{2.361 \times 10^{-8}}} = \frac{1}{0.133 \times 10^3 W + 1.385 \times 10^3 W^2}
\]

\[
\beta (W = 5 \mu m) = \frac{1}{0.133 \times 10^{-2} + 0.1385 \times 10^{-2}} = \frac{1}{0.272 \times 10^{-2}} = 368
\]

\[
\beta (W = 5 \mu m) = \frac{1}{0.133 \times 10^{-2} \times 5 + 0.1385 \times 10^{-2} \times 25} = \frac{1}{(0.665 + 3.4625) \times 10^{-2}} = 24.2
\]
Obtain $I_C$, $I_B$, $V_{BE}$, and the minority charge stored in the base in above problem if $W = 2 \mu m$, and $I_C = 1$ mA.

**Solution:**

\[
I_S = \frac{3834 \times 10^{-24}}{W} = \frac{3834 \times 10^{-24}}{2 \times 10^{-4}}
\]

\[
= 1.917 \times 10^{-20} A,
\]

$\beta(W = 2 \mu m)$

\[
= \frac{1}{0.133 \times 10^{-2} \times 2 + 0.1385 \times 4 \times 10^{-2}}
\]

\[
= \frac{1}{(0.266 + 0.554) \times 10^{-2}} = \frac{100}{0.82} = 122
\]

\[
I_B = \frac{I_C}{\beta} = \frac{1mA}{122} = 8.197 \mu A, I_E = I_C + I_B
\]

\[
= 1mA + 0.0082 mA = 1.008 mA
\]

\[
V_{BE} = V_T \ln \frac{I_C}{I_S} = 0.026 \ln \frac{10^{-3}}{1.917 \times 10^{-20}}
\]

\[
= 0.026 \ln \frac{10^7}{1917} = 0.026 \ln \left( \frac{52 \times 10^{10}}{1} \right)
\]

\[
= 0.026 \times 38.493 = 1 V
\]

\[
Q_n = \frac{1}{2} \frac{qA_B W n_e^2}{N_A} \exp \frac{q \phi_F}{kT} = \frac{1}{2} \frac{qA_B W n_e^2}{N_A} \frac{I_C}{I_S}
\]

\[
= \frac{1}{2} \frac{1}{213} \frac{4 \times 10^{-14}}{4.9262 \times 10^{11}} = 0.094 \times 10^{-11}
\]

\[
= 0.94 pC
\]

Two BJTs of different junction areas, fabricated using the same technology, operated at $V_{BE} = 0.7 V$ yield collector currents of 0.13 mA and 10.9 mA. Obtain $I_S$ for each device. What is the relative junction area?

\[
I_{S1} = I_{S1} \exp \frac{V_{BE}}{V_T} = I_{S1} \exp^{0.7 \times 0.026}
\]

\[
= I_{S1} \exp^{26.923} = 4.9262 \times 10^{11} I_{S1}
\]

\[
I_{S1} = 0.13 \times 10^{-3}
\]

\[
= \frac{0.13 \times 10^{-14}}{4.9262 \times 10^{11}} = 0.0264 \times 10^{-14} A, I_{S2} = \frac{10.9 \times 10^{-3}}{4.9262 \times 10^{11}}
\]

\[
= 2.213 \times 10^{-14} A
\]

Relative junction area $= \frac{I_{S2}}{I_{S1}}$

\[
= \frac{2.213 \times 10^{-14} A}{0.0264 \times 10^{-14} A} = 83.8
\]
28. The collector current of an n-p-n transistor are 1mA and 10 mA for base-emitter voltages of 0.63 V and 0.7 V. Obtain corresponding values of $\eta$ and $I_S$. What is total collector current if two such devices are connected in parallel as in Fig. 5.30 and base emitter voltage $V_{BE} = 0.67$ V is applied across them?

\[ I_{C1} = I_S \exp \frac{V_{BE}}{\eta V_T} \] and
\[ I_{C2} = I_S \exp \frac{V_{BE}}{\eta V_T} \]
\[ \frac{I_{C2}}{I_{C1}} = \exp \frac{V_{BE}}{\eta V_T} = \exp ^{0.7/1.2 \times 0.006} \]
\[ = 10 \ \text{mA} \]
\[ \frac{1 \ \text{mA}}{1 \ \text{mA}} \]
\[ \frac{V_{BE2} - V_{BE1}}{\eta V_T} = \ln 10 = 2.3, \]
\[ \eta = \frac{0.7 - 0.63}{2.3 \times 0.026} = \frac{0.07}{2.3 \times 0.026} = 1.2 \]
\[ I_{C1} = I_S \exp \frac{V_{BE}}{\eta V_T} = I_S \exp ^{0.7/1.2 \times 0.006} \]
\[ = I_S \exp ^{1.2} = 5.5432 \times 10^9 I_S \]
\[ I_S = \frac{10 \times 10^{-3}}{5.543 \times 10^9} = 1.8 \times 10^{-13} \text{A}, \]
\[ I_C = 2 \times 1.8 \times 10^{-13} \exp ^{0.65/1.2 \times 0.026} \]
\[ I_{C1} + I_{C2} = 2 \times 1.8 \times 10^{-13} \exp ^{20.833} \]
\[ = 2 \times 1.8 \times 10^{-13} \times 1.12 \times 10^9 \]
\[ = 4.02 \times 10^{-4} \text{A} = 0.402 \text{mA}. \]

Figure 5.30

29. The emitter current of an n-p-n transistor at $V_{BE} = 0.7$ V and temperature 25°C is 1 mA. What would be the value of base-emitter voltage at 0°C and 100°C.

**Solution:**

We know that the $V_{BE}$ decreases linearly with increasing temperature at a rate = 2.5 mV/°C.

Hence, $V_{BE} (0°C) = 0.7 V + 0.0025 \times 25 = 0.7625 V$

$V_{BE} (100°C) = 0.7 V - 0.0025 \times 75 = 0.5125 V$
The emitter current of an n-p-n transistor at $V_{BE} = 0.7$ V and temperature 20°C is 0.5 mA. What would be the value of base-emitter voltage if the junction temperature rises to 50°C? What emitter current can flow for $V_{BE} = 0.705$ V at temperature 20°C and 100°C?

**Solution:**

$V_{BE}$ changes by 0.0025V in 1°C change. Hence, change in $V_{BE}$ (50°C) = 0.7 − 0.0025(50 − 20) = 0.625 V. At 20°C, $I_E = 0.5$ mA for $V_{BE} = 0.7$ V, then at 20°C for $V_{BE} = 0.75$ V, $I_E$ = ?

$$\frac{I_{C2}(0.705 \text{ V})}{I_{C1}(0.7 \text{ V})} = \exp^{(705-700)/26} = \exp^{0.26}$$

$$= \exp^{0.1923}$$

$$I_{C2} = I_{C1}(0.7 \text{ V})\exp^{0.1923}$$

$$= 0.5 \times 1.212 = 0.6 \text{ mA}$$

$$\frac{I_{C2}(0.705 \text{ V})}{I_{C1}(0.625 \text{ V})} = \exp^{(705-700)/26} = \exp^{0.369}$$

$$= 26.29$$

$I_{C2}(0.705 \text{ V})$ at 100°C = $0.5 \times 26.29$ = 13.15 mA

An n-p-n transistor operating at $I_C = 2$ mA and $V_{BE} = 0.7$ V and its $I_C - V_{CE}$ characteristic has slope of $5 \times 10^{-3}$ S. What would be the corresponding values of the output resistance and early voltage? What would happen to the output resistance if $I_C$ becomes 20 mA?

**Solution:**

$$r_o = \frac{1}{\text{slope}} = 20 \text{ K\Omega}, V_A = r_o I_C = 20 \times 2$$

$$= 40 \text{ V}, r_o = \frac{V_A}{20 \text{ mA}} = \frac{40 \text{ V}}{20 \text{ mA}} = 2 \text{ K\Omega}$$

What would be the Early voltage if the output resistance of a BJT at collector current of 10 μA is 10 MΩ? How much the output resistance would become, if the collector current is raised to 10 mA?

**Solution:**

$$V_A = r_o I_C = 10 \times 10 = 100 \text{ V},$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{10 \text{ mA}} = 10 \text{ K\Omega}$$

The base-emitter voltage ($V_{BE}$) in Fig. 5.31 is adjusted such that it results into $I_C = 1$ mA and $V_{CE} = 2$ V. The $V_{CE}$ is raised to 10V keeping the $V_{BE}$ constant that results in $I_C = 1.1$ mA. Obtain $V_A$ and $r_o$ of the BJT at $I_C = 1$ mA.

**Solution:**

Slope of the $I_C - V_{CE}$ curve = \frac{1.1 - 1}{10 - 2} = \frac{0.1 \times 10^{-3}}{8}, r_o = 80 \text{ K\Omega}, \frac{0.1 \times 10^{-3}}{8} = \frac{1 \text{ mA}}{V_A} \Rightarrow V_A = \frac{1 \times 10^{-3}}{0.1 \times 10^{-3}} \times 8 = 80 \text{ V}

**Figure 5.31**
Find the values of $V_E$ and $V_C$ for $V_B = 3 \text{ V}$, $1 \text{ V}$, and $0 \text{ V}$ assuming very high value of current amplification factor $\beta$ in Fig. 5.31.

**Solution:**

\[
V_B - V_{BE} = V_E = 5 - 0.7 = 2.3 \text{ V},
\]

\[
I_E = 2.3 \text{ mA} = I_C \text{ (for very high $\beta$)},
\]

\[
V_C = 9 \text{ V} - 2.3 \text{ V} = 6.7 \text{ V}
\]

\[
V_B = 1 \text{ V}, V_E = 0.3 \text{ V}, I_E = 0.3 \text{ mA} = I_C
\]

(for very high $\beta$), $V_C = 9 \text{ V} - 0.3 \text{ V}
\]

\[= 8.7 \text{ V}
\]

$V_B = 0 \text{ V}, V_E = -0.7 \text{ V}, \text{BJT is reverse biased and cut-off, } I_E = 0 = I_C, V_B = 0 \text{ V},$

$V_C = 9 \text{ V}$

35 The emitter voltage $V_E$ in Fig. 5.32 measures to be $-1 \text{ V}$. What are the values of $V_B$, $I_B$, $I_C$, $I_E$, $V_C$, $\alpha$ and $\beta$?

**Solution:**

\[
V_B = V_{BE} + V_E = 0.7 \text{ V} - 1 \text{ V} = -0.3 \text{ V},
\]

\[
I_B = \frac{0.3}{20 \text{ K}} = 0.015 \text{ mA},
\]

\[
I_E = \frac{5 - 1}{3 \text{ K}} = 0.8 \text{ mA},
\]

\[
I_C = 0.8 - 0.015 = 0.785 \text{ mA},
\]

\[
V_C = 5 - 3.925 = 1.1 \text{ V},
\]

\[
\alpha = \frac{I_C}{I_E} = \frac{0.785}{0.8} = 0.99
\]

\[
\beta = \frac{0.785}{0.015} = 52.33
\]

![Figure 5.32](image)

36 The nominal value of $g_m$ of a BJT is $80 \text{ mS}$ whose $\beta$ falls in the range of $50$ to $200$. The actual variation in the collector current $I_C$ is $20\%$. What would be the extreme values of resistance looking into the base of the BJT?

**Solution:**

The simplest hybrid-$\pi$ model of the BJT at low frequency is drawn as in Fig. 5.33. The resistance seen by the base of the BJT is $r_n$.

\[
g_{m(\text{max})} = g_m + 0.20 g_m = g_m(1.2)
\]

\[
= 80 \text{ mS} \times 1.2 = 96 \text{ mS}
\]

\[
g_{m(\text{min})} = g_m - 0.20 g_m = 0.8 g_m = 64 \text{ mS}
\]

\[
r_{g(\text{max})} = \frac{\beta_{\text{max}}}{g_{m(\text{max})}} = \frac{200}{64} = 3.125 \text{ K}\Omega
\]

\[
r_{g(\text{min})} = \frac{\beta_{\text{min}}}{g_{m(\text{min})}} = \frac{50}{96} = 0.52 \text{ K}\Omega
\]

![Figure 5.33](image)
37 The $V_{be}$ in the circuit of Fig. 5.34 is adjusted such that $V_C = 2$ V. Obtain the instantaneous quantities such as $i_C(t)$, $v_C(t)$, and $i_B(t)$, if $V_{CC} = 10$ V, $R_C = 2$ KΩ, and a signal of $v_{be} = 0.004 \sin \omega t$ is applied.

**Solution:**

\[
I_C = \frac{V_{CC} - V_C}{R_C} = \frac{10 - 2}{2} = 4 \text{ mA},
\]

\[
g_m = \frac{I_C}{V_T} = 0.16 \text{ S}
\]

\[
i_C(t) = I_C + g_m v_{be}(t)
\]

\[
= 4 + 160 \times 0.004 \sin \omega t
\]

\[
= (4 + 0.64 \sin \omega t) \text{mA}
\]

\[
v_C(t) = 10 - R_C I_C(t) = 10 - 8 - 1.28 \sin \omega t
\]

\[
= (2 - 1.28 \sin \omega t) \text{V}
\]

\[
i_B(t) = \frac{i_C(t)}{\beta} = \frac{(4 + 0.64 \sin \omega t) \text{mA}}{100}
\]

\[
= (0.04 + 0.006 \sin \omega t) \text{mA}
\]

Voltage gain $= \frac{-1.28}{0.004} = -320$

**Figure 5.34**

![Circuit Diagram]

38 In Fig. 5.34 if $V_{CC}$ is fixed at 10 V and input signal $v_{be} = V_{be(max)} \sin \omega t$ is applied to maintain linearity for amplification, then show that the largest signal at the collector without the BJT leaving the active region is given by

\[
R_{CL} = \frac{(V_{CC} - V_{BE} - V_{be(max)})}{1 + \frac{V_{be(max)}}{V_T}}
\]

Obtain the dc voltage at the collector and voltage gain of the amplifier.

**Solution:**

Input voltage $= V_{be} + V_{be(max)} \sin \omega t$, $v_C = V_{CC} - I_C R_C - g_m V_{be(max)} \sin \omega t R_C$

In order to maintain the BJT in the active region, $v_C \geq v_{be}$, then

\[
V_{CC} - V_C - g_m V_{be(max)} = V_C - V_{be(max)} \sin \omega t
\]

To obtain the maximum output signal the equality sign in the above equation is equated
A BJT amplifier in Fig. 5.35 is biased with a constant current source $I$ and has very high $\beta$. Obtain dc voltage at the collector and voltage gain of the amplifier. In equivalent circuit, an open circuit should replace the current source.

**Solution:**

$I_E = I_C = 1\text{mA (high } \beta)$

$V_C = 5 - 2 = 3\text{V}$

$g_m = \frac{I_c}{V_T} = \frac{1}{25} = 0.04S$

$v_x + v_{\pi} = 0, \quad v_x = -v_{\pi}$

$v_c = g_mR_v v_x = -0.04 \times 2 K v_{\pi}$

$v_c = -0.040 \times 2 K v_{\pi} = -40 \times 2 v_{\pi}$

Voltage gain $= \frac{v_c}{v_{\pi}} \times \frac{v_{\pi}}{v_x} = 80 = \frac{v_c}{v_x}$

![Figure 5.35](image)
40. What should be the ac input voltage and current to develop 1.5 V peak-to-peak across the output terminals of the circuit shown in Fig. 5.36. Given $g_m = 100$ mS and $\theta = 100$.

**Solution:**
\[
\begin{align*}
v_e &= g_m R_C V_{be} = -100 \times 2 V_{be} = -200 V_{be} \\
v_{be} &= \frac{1.5}{200} = 75 \text{ mV} \\
i_b &= \frac{V_{be}}{r_e} = \frac{V_{be}}{\beta g_m} = \frac{100 \times 75}{100} = 75 \mu A.
\end{align*}
\]

41. The emitter-base junction saturation current of a BJT having $\alpha_F = 1$ and $\alpha_R = 0.1$ is $10^{-14}$ A. What would be the value of its collector-base junction saturation current? What is the relative size of the collector junction with respect to the emitter junction? How much is the value of $\beta_R$?

**Solution:**
\[
\begin{align*}
I_{se} \alpha_F &= \alpha_R I_{sc} \\
I_{se} = \frac{\alpha_F}{\alpha_R} &= \frac{10^{-14}}{0.1} \\
\text{Area of collector junction} &= \frac{I_{sc}}{I_{se}} \\
\text{10-times the area of emitter junction} \\
\beta_R &= \frac{\alpha_R}{1 - \alpha_R} = \frac{0.1}{1 - 0.1} = 0.111
\end{align*}
\]

42. Both BJTs in Figs. 5.37 (a) and (b) are identical and current $i$ is set equal to $I$ for $V_{ce} = 0.7$ V in Fig. 5.37 (a) and in Fig. 5.37 (b) for $V_{ce} = 0.6$ V. Obtain relative size of emitter-base and collector-base junction.

**Solution:**
\[
\begin{align*}
I_{se} = V_{be} = V_{bc} = V_{ce} \\
i_e &= \frac{I_{se}}{\alpha_F} = \frac{I_{se}}{\exp\left(V_{ce}/V_T - 1\right)} \\
i &= \frac{I_{se}}{\alpha_F} = \frac{I_{se}}{\exp^{70/26} - 1} = \frac{I_{sc}}{\alpha_R} = \frac{I_{se}}{\exp^{9/11} - 1} \\
I_{se} = \frac{I_{sc}}{\alpha_F} = \frac{26.923}{\exp^{70/26} - 1} = \frac{4.9266 \times 10^{11}}{\alpha_R} \\
\text{In Fig. 5.42, } I_c &= -I = I_{sc} \exp^{\alpha_R/\alpha_F - 1} \\
&= \frac{I_{se}}{\alpha_R} = \frac{I_{se}}{\exp^{600/26} - 1} \\
i &= \frac{I_{se}}{\alpha_R} = \frac{23.077}{\exp^{23.077} - 1} = I_{sc} \times 10524 \times 10^{-10} \\
\text{Hence, } I_{se}/I_{sc} &= 4.93 \times 10^{11} \\
o_r \alpha_e &= \frac{I_{se}/I_{sc}}{\alpha_R} = \frac{49.3}{10524} = 46.85
\end{align*}
\]

The collector-base junction is 46.85 times the emitter-base junction.
Obtain relationship between $i_b$ and $i_E$ for a diode connected BJT shown in \textbf{Fig. 5.38}.

\textbf{Solution:}

$V_{BE} = V_{BC} = V > 0$, From Eqn. (5.9.11),

$$i_b = \frac{I_E}{\beta_F} (\exp^{V_{BE}/V_T} - 1) + \frac{I_E}{\beta_R} (\exp^{V_{BE}/V_T} - 1)$$

$$i_b = \frac{I_E}{\beta_F} \exp^{V_{BE}/V_T} + \frac{I_E}{\beta_R} \exp^{V_{BE}/V_T}$$

$$= \left( \frac{I_E}{\beta_F} + \frac{I_E}{\beta_R} \right) \exp^{V_{BE}/V_T}$$

$$= \frac{I_S (\beta_F + \beta_R)}{\beta_F \beta_R} \exp^{V_{BE}/V_T}$$

or, \( \frac{I_S}{\beta_F} \exp^{V_{BE}/V_T} = i_b \frac{\beta_R}{\beta_R + \beta_F} \)

From Eqn. (5.9.9),

$$i_E = \frac{I_S}{\alpha_F} \exp^{V_{BE}/V_T} - I_S \exp^{V_{BE}/V_T}$$

$$= I_S \left( \frac{1}{\alpha_F} - 1 \right) \exp^{V_{BE}/V_T} = \frac{I_S}{\beta_F} \exp^{V_{BE}/V_T}$$

or, \( \frac{I_S}{\beta_F} \exp^{V_{BE}/V_T} = i_b \frac{\beta_R}{\beta_R + \beta_F} \)

$$= i_b \frac{\beta_R}{\beta_F}$$

\textbf{Figure 5.38}

What would be the values of $\beta_F$ and $\beta_R$ of a BJT with its fixed base current that produces $V_{CE(SAT)} = 0.080$ V when its emitter terminal is grounded and collector terminal is left open and produces $V_{CE(SAT)} = 0.001$
V when its collector terminal is grounded and emitter terminal is left open?

**Solution:**

From Eqn. (5.9.19) $V_{CE(SAT)}$

$$V_{CE(SAT)} = V_2 \ln \frac{1 + (\beta_{forced} + 1)/\beta_R}{1 - \beta_{forced}/\beta_F}$$

With emitter grounded and collector open circuited, $\theta_{forced} = 0$,

$$V_{CE(SAT)} = 0.080 = 0.026 \ln \frac{1 + (0 + 1)/\beta_R}{1 - 0/\beta_F}$$

$$= 0.026 \ln \frac{1 + \beta_R}{1} \ln (1 + 1/\beta_R)$$

$$= \frac{80}{26} = 3.1$$

or, $1 + \frac{1}{\beta_R} = \exp 3.1 = 22.198$

$$\beta_R = \frac{1}{22.198} = 0.047$$

When collector is grounded and emitter is left opened, $\theta_{forced} = 0, \theta_F = \theta_R$. 