

**Example-** At 300 K, the silicon npn bipolar junction transistor (BJT) from the earlier example has the following parameters:

Emitter ( <i>n</i> -region)	Base ( <i>p</i> -region)	Collector ( <i>n</i> -region)
$n_{E0} \cong N_E = 10^{18} \text{ cm}^{-3}$	$p_{B0} \cong N_B = 10^{16} \text{ cm}^{-3}$	$n_{C0} \cong N_C = 10^{15} \text{ cm}^{-3}$
$p_{E0} = 225 \text{ cm}^{-3}$	$n_{B0} = 22,500 \text{ cm}^{-3}$	$p_{C0} = 225,000 \text{ cm}^{-3}$
$\mu_{nE} = 280 \text{ cm}^2/\text{V-s}$	$\mu_{pB} = 420 \text{ cm}^2/\text{V-s}$	$\mu_{nC} = 1200 \text{ cm}^2/\text{V-s}$
$D_E = 7.24 \text{ cm}^2/\text{s}$	$D_B = 10.86 \text{ cm}^2/\text{s}$	$D_C = 31.02 \text{ cm}^2/\text{s}$
$L_E = 2.69 \text{ }\mu\text{m}$	$L_B = 7.37 \text{ }\mu\text{m}$	$L_C = 17.61 \text{ }\mu\text{m}$
$\tau_{E0} = 10 \text{ ns}$	$\tau_{B0} = 50 \text{ ns}$	$\tau_{C0} = 100 \text{ ns}$
$x_E = 1.5 \text{ }\mu\text{m}$	$x_B = 0.75 \text{ }\mu\text{m}$	$x_C = 90 \text{ }\mu\text{m}$

Also,  $A_{BE} = 5 \times 10^{-3} \text{ cm}^2 = 5 \times 10^{-8} \text{ m}^2$ ,  $V_{BE} = 0.64 \text{ V}$ , and  $V_{CE} = 5 \text{ V}$ .

From Table B.4,  $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$  &  $\epsilon_s = 11.7 \epsilon_0$  at 300 K.

At 300 K, (7.10)  $V_t = k_B T / e = 0.025852 \text{ V}$ .

Find the emitter currents and contributions from electrons & holes as well as the common-base & common-emitter current gains.

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### Currents from BE junction (forward-biased)

Using the expression for the excess holes at  $x' = 0$  (emitter side of BE depletion region), we can compute the **hole current density** using (12.33a) & (12.34a)

$$\begin{aligned}
 J_{pE} = J_p(x' = 0) &= -eD_E \left. \frac{d\delta p_E(x')}{dx'} \right|_{x'=0} = \frac{eD_E p_{E0}}{L_E} \left[ e^{V_{BE}/V_t} - 1 \right] \frac{1}{\tanh(x_E / L_E)} \\
 &= \frac{1.6022 \cdot 10^{-19} (7.24 \cdot 10^{-4}) 225 \cdot 10^6}{2.69 \cdot 10^{-6}} \left[ e^{0.64/0.025852} - 1 \right] \frac{1}{\tanh(1.5 / 2.69)} \\
 &\Rightarrow \underline{J_{pE} = 1081.373 \text{ A/m}^2}.
 \end{aligned}$$

Then, the **hole current** is  $I_{pE} = J_{pE} (A_{BE}) = 1081.373 (5 \times 10^{-8})$

$$\Rightarrow \underline{I_{pE} = 5.406865 \times 10^{-5} \text{ A} = 0.05407 \text{ mA}}.$$

Using the expression for the excess electrons at  $x = 0$  (base side of BE depletion region), we can compute the **electron current density** using (12.33b) & (12.34b)

$$\begin{aligned}
 J_{nE} = J_n(x=0) &= -eD_B \left. \frac{d\delta n_B(x)}{dx} \right|_{x=0} = \frac{eD_B n_{B0}}{L_B} \left\{ \frac{1}{\sinh(x_B / L_B)} + \frac{e^{V_{BE}/V_i} - 1}{\tanh(x_B / L_B)} \right\} \\
 &= \frac{1.6022 \cdot 10^{-19} (10.86 \cdot 10^{-4}) 22,500 \cdot 10^6}{7.37 \cdot 10^{-6}} \left\{ \frac{1}{\sinh(0.75 / 7.37)} + \frac{e^{0.64/0.025852} - 1}{\tanh(0.75 / 7.37)} \right\} \\
 &\Rightarrow \underline{J_{nE} = 2.955277 \times 10^5 \text{ A/m}^2}.
 \end{aligned}$$

Then, the **electron current** is  $I_{nE} = J_{nE} (A_{BE}) = 2.955277 \times 10^5 (5 \times 10^{-8})$

$$\Rightarrow \underline{I_{nE} = 0.0147764 \text{ A} = 14.7764 \text{ mA}}.$$

The **overall emitter current density** and **emitter current**

$$J_E = J_{pE} + J_{nE} = 1081.373 + 2.955277 \times 10^5 \Rightarrow \underline{J_E = 2.96609 \times 10^5 \text{ A/m}^2}.$$

$$I_E = I_{pE} + I_{nE} = 5.406865 \times 10^{-5} + 0.0147764 \Rightarrow \underline{I_E = 0.01483 \text{ A} = 148.3045 \text{ mA}}.$$

Note the relative contributions of electrons and holes to the emitter current in an npn BJT-

$$\% \text{ electrons} = \frac{J_{nE}}{J_E} (100\%) = \frac{2.955277 \times 10^5}{2.966091 \times 10^5} (100\%) \Rightarrow \underline{99.635\%}.$$

$$\text{and } \% \text{ holes} = \frac{J_{pE}}{J_E} (100\%) = \frac{1081.373}{2.966091 \times 10^5} (100\%) \Rightarrow \underline{0.365\%}.$$

Obviously, the electrons are the dominant component of the overall emitter current.

To find the common-base  $\alpha$  and common-emitter  $\beta$  current gains, we will need the parameters  $V_{bi}$ ,  $x_{BE}$ ,  $\tau_0$ ,  $J_{r0}$ ,  $J_{s0}$ ,  $\alpha_T$ ,  $\gamma$ , and  $\delta$ .

Per (7.10), the built-in voltage for the BE junction is:

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_B N_E}{n_i^2}\right) = 0.025852 \ln\left(\frac{10^{16} (10^{18})}{(1.5 \times 10^{10})^2}\right) \Rightarrow \underline{V_{bi} = 0.8124 \text{ V.}}$$

Per a modified (7.34), the width of the forward-biased BE junction is:

$$\begin{aligned} x_{BE} &= \left\{ \frac{2\epsilon_s (V_{bi} - V_a)}{e} \left[ \frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2} = \left\{ \frac{2\epsilon_s (V_{bi} - V_{BE})}{e} \left[ \frac{N_B + N_E}{N_B N_E} \right] \right\}^{1/2} \\ &= \left\{ \frac{2(11.7)8.8541878 \times 10^{-12} (0.8124 - 0.64)}{1.602176634 \times 10^{-19}} \left[ \frac{10^{22} + 10^{24}}{10^{22} (10^{24})} \right] \right\}^{1/2} \\ &\Rightarrow \underline{x_{BE} = 1.50057 \times 10^{-7} \text{ m}} \end{aligned}$$

(Yikes! This is a significant fraction of  $x_B$  &  $x_E$ . We are going to assume the given  $x_B$  &  $x_E$  are in addition to the BE depletion layer, ala Figure 12.13.)

Per (8.39), the average lifetime for the BE junction is:

$$\tau_0 = (\tau_{E0} + \tau_{B0}) / 2 = (10 + 50) / 2 \Rightarrow \underline{\tau_0 = 30 \text{ ns.}}$$

Per (12.41),

$$\begin{aligned} J_{r0} &= \frac{e x_{BE} n_i}{2\tau_0} = \frac{1.60218 \times 10^{-19} (1.5 \times 10^{-7}) 1.5 \times 10^{16}}{2(30 \times 10^{-9})} \\ &\Rightarrow \underline{J_{r0} = 6.01045 \times 10^{-3} \text{ A/m}^2.} \end{aligned}$$

$$\begin{aligned} \text{Per (12.43), } J_{s0} &= \frac{e D_B n_{B0}}{L_B \tanh(x_B / L_B)} = \frac{1.6022 \times 10^{-19} (10.86 \times 10^{-4}) 22500 \cdot 10^6}{7.37 \times 10^{-6} \tanh(0.75 / 7.37)} \\ &\Rightarrow \underline{J_{s0} = 5.237898 \times 10^{-6} \text{ A/m}^2.} \end{aligned}$$

Per (12.39a), the **base transport factor** is

$$\alpha_T = 1 / \cosh(x_B / L_B) = 1 / \cosh(0.75 / 7.37) \Rightarrow \underline{\alpha_T = 0.9948443}.$$

Per (12.35a), the **emitter injection efficiency** is

$$\gamma = \frac{1}{1 + \frac{p_{E0} D_E L_B \tanh(x_B / L_B)}{n_{B0} D_B L_E \tanh(x_E / L_E)}} = \frac{1}{1 + \frac{225(7.24)7.37 \tanh(0.75 / 7.37)}{22500(10.86)2.69 \tanh(1.5 / 2.69)}} \Rightarrow \underline{\gamma = 0.9963541}.$$

Per (12.44), the **recombination factor** is

$$\delta = \frac{1}{1 + \frac{J_{r0}}{J_{s0}} e^{-V_{BE}/2V_t}} = \frac{1}{1 + \frac{6.0104455 \times 10^{-3}}{5.237898 \times 10^{-6}} e^{-0.64/2(0.025852)}} \Rightarrow \underline{\delta = 0.9951928}.$$

Per (12.30b), the **common-base current gain** is

$$\alpha = \gamma \alpha_T \delta = 0.9963541 (0.9948443) 0.9951928 \Rightarrow \underline{\alpha = 0.986452}.$$

Per Table 12.3, the **common-emitter current gain** is

$$\beta = \alpha / (1 - \alpha) = 0.986452 / (1 - 0.986452) \Rightarrow \underline{\beta = 72.813}.$$