Problem Solutions

Chapter Four: Bipolar Junction Transistors

P4.1. Estimate β_F for an npn bipolar transistor assuming that the emitter injection efficiency and the collector multiplication factor are both unity. The base width is 120 nm, the base doping is 10^{18} cm^{-3} and the base minority carrier lifetime is 1.0 ns.

Solution. If the base doping is 10^{18} cm^{-3}, the electron mobility in the base can be determined from Figure 2.8 to be

$$\mu_n \approx 250 cm^2 V^{-1} s^{-1}.$$

Using the Einstein relationship, the diffusivity of electrons in the base is

$$D_{nB} = \frac{kT}{q}\mu_n = (0.026V)(250 cm^2 V^{-1} s^{-1}) = 6.5 cm^2 s^{-1}.$$

The diffusion length for electrons in the base is

$$L_{nB} = \sqrt{D_{nB}\tau_{nB}} = \sqrt{(6.5 cm^2 s^{-1})(10^{-9} s)} = 8.1\times 10^{-5} cm.$$

The base transport factor is

$$\alpha_T \approx \left(1 + \frac{W_B^2}{2L_{nB}^2}\right)^{-1} = \left(1 + \frac{(120\times 10^{-7} cm)^2}{2(8.1\times 10^{-5} cm)^2}\right)^{-1} = 0.989.$$

Assuming that the emitter injection efficiency and the collector multiplication factor are both unity,

$$\alpha_F \approx M\gamma_E\alpha_T \approx \alpha_T = 0.989,$$

and the common base current gain is

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.989}{1-0.989} = 90.$$

P4.2. Estimate β_F for a lateral pnp bipolar transistor assuming that emitter injection efficiency and the collector multiplication factor are both unity. The base width is 250 nm, the base doping is 10^{17} cm^{-3} and the base minority carrier lifetime is 3.0 ns.

Solution. If the base doping is 10^{17} cm^{-3}, the hole mobility in the base can be determined from Figure 2.8 to be 300 cm^{2}V^{-1}s^{-1}. Using the Einstein relationship, the diffusivity of holes in the base is

$$D_{pB} = \frac{kT}{q}\mu_{pB} = (0.026V)\left(300cm^2V^{-1}s^{-1}\right) = 7.8cm^2s^{-1}.$$

The diffusion length for holes in the base is

$$L_{pB} = \sqrt{D_{pB}\tau_{pB}} = \sqrt{\left(7.8cm^2s^{-1}\right)\left(3\times10^{-9}s\right)} = 1.53\times10^{-4}cm.$$

The base transport factor is

$$\alpha_T \approx \left(1+\frac{W_B^2}{2L_{nB}^2}\right)^{-1} = \left(1+\frac{\left(250\times10^{-7}cm\right)^2}{2\left(7.8\times10^{-5}cm\right)^2}\right)^{-1} = 0.95.$$

Assuming that the emitter injection efficiency and the collector multiplication factor are both unity,

$$\alpha_F \approx M\gamma_E\alpha_T \approx \alpha_T = 0.95,$$

and the common base current gain is

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{1-0.95} = 19.$$

P4.3. Estimate the base transit time for an npn bipolar transistor if the undepleted base width is 120 nm and the base doping is 10^{18} cm^{-3}.

Solution. If the base doping is 10^{18} cm^{-3}, the electron mobility in the base can be determined from Figure 2.8 to be

$$\mu_n \approx 250 cm^2 V^{-1} s^{-1}.$$

Using the Einstein relationship, the diffusivity of electrons in the base is

$$D_{nB} = \frac{kT}{q}\mu_n = (0.026V)(250 cm^2 V^{-1} s^{-1}) = 6.5 cm^2 s^{-1}.$$

The base transit time is

$$t_{tB} = \frac{W^2}{2D_{nB}} = \frac{(120\times 10^{-7} cm)^2}{2(6.5 cm^2 V^{-1} s^{-1})} = 11.1 ps.$$

P4.4. Estimate the base transit time for a lateral pnp bipolar transistor if the undepleted base width is 250 nm and the base doping is 10^{17} cm^{-3}.

Solution. If the base doping is 10^{18} cm^{-3}, the electron mobility in the base can be determined from Figure 2.8 to be 300 cm^{2}V^{-1}s^{-1}. Using the Einstein relationship, the diffusivity of electrons in the base is

$$D_{pB} = \frac{kT}{q}\mu_p = (0.026V)(300 cm^2 V^{-1} s^{-1}) = 7.8 cm^2 s^{-1}.$$

The base transit time is

$$t_{tB} = \frac{W^2}{2D_{nB}} = \frac{(250\times 10^{-7} cm)^2}{2(7.8 cm^2 V^{-1} s^{-1})} = 40 ps.$$

P4.5. Estimate the reverse saturation current for an npn bipolar transistor if the undepleted base width is 120 nm, the base doping is 10^{18} cm^{-3}, the base minority carrier lifetime is 1.0 ns, and the emitter area is 10^{-4} cm^2.

Solution. If the base doping is 10^{18} cm^{-3}, the electron mobility in the base can be determined from Figure 2.8 to be

$$\mu_n \approx 250 cm^2 V^{-1} s^{-1}.$$

Using the Einstein relationship, the diffusivity of electrons in the base is

$$D_{nB} = \frac{kT}{q}\mu_n = (0.026V)\left(250 cm^2 V^{-1} s^{-1}\right) = 6.5 cm^2 s^{-1}.$$

The saturation current is

$$I_S = \frac{qAD_{nB}n_i^2}{W_B N_{aB}}$$

$$= \frac{\left(1.602\times10^{-19}C\right)\left(10^{-4}cm^{-2}\right)\left(6.5cm^2 s^{-1}\right)\left(1.45\times10^{10}cm^{-3}\right)^2}{\left(120\times10^{-7}cm\right)\left(10^{18}cm^{-3}\right)}.$$

$$= 1.82\times10^{-15} A$$

P4.6. Estimate the emitter area for an npn bipolar transistor if the forward active collector current is 1 mA with a base-emitter voltage of 0.75 V. The base width is 180 nm and the base doping is 10^{17} cm^{-3}. Assume the forward emission coefficient is unity and the series resistances are negligible.

Solution. Assuming the emission coefficient is unity,

$$I_S = \frac{I}{\exp(qV/kT)} = \frac{10^{-3}A}{\exp(0.75V/0.026V)} = 3.0\times10^{-16}A.$$

If the base doping is 10^{17} cm^{-3}, the electron mobility in the base can be determined from Figure 2.8 to be

$\mu_n \approx 800 cm^2 V^{-1} s^{-1}$.

Using the Einstein relationship, the diffusivity of electrons in the base is

$$D_{nB} = \frac{kT}{q}\mu_n = (0.026V)(800 cm^2 V^{-1} s^{-1}) = 21 cm^2 s^{-1}.$$

The saturation current per unit area is

$$\frac{I_S}{A} = \frac{qD_{nB} n_i^2}{W_B N_{aB}}$$
$$= \frac{(1.602\times10^{-19} C)(21 cm^2 s^{-1})(1.45\times10^{10} cm^{-3})^2}{(180\times10^{-7} cm)(10^{17} cm^{-3})}.$$
$$= 3.9\times10^{-10} Acm^{-2}$$

The emitter area can be estimated as

$$A = \frac{I_S}{I_S / A} = \frac{3.0\times10^{-16} A}{3.9\times10^{-10} Acm^{-2}} = 7.7\times10^{-7} cm^2.$$

P4.7. For the bipolar transistor in the circuit of Figure 4.16, determine the mode of operation and the collector-emitter voltage.

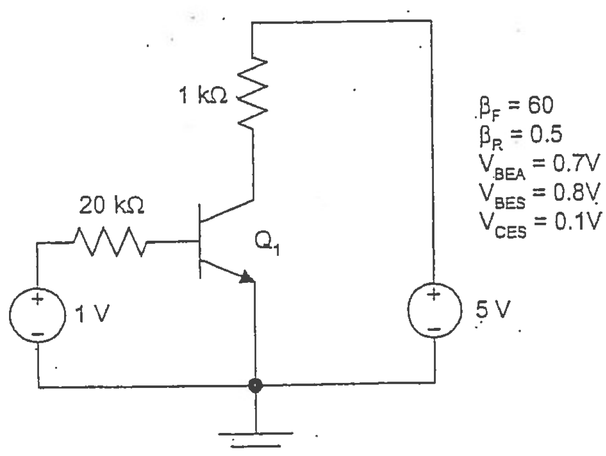

Figure 4.16.

Solution. Assuming forward active operation,

$$I_B = \frac{1V - 0.7V}{20k\Omega} = 0.015mA,$$

$$I_C = \beta_F I_B = (60)(0.015mA) = 0.9mA, \text{ and}$$

$$V_{CE} = 5V - (1k\Omega)(0.9mA) = 4.1V.$$

Therefore, the initial assumption was correct and the transistor is forward active.

P4.8. For the bipolar transistor in the circuit of Figure 4.17, determine the collector current.

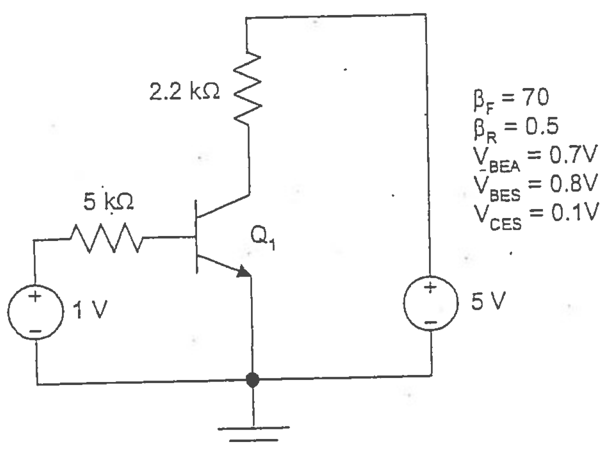

Figure 4.17.

Solution. Assuming forward active operation,

$$I_B = \frac{1V - 0.7V}{5k\Omega} = 0.06mA,$$

$$I_C = \beta_F I_B = (70)(0.06mA) = 4.2mA, \text{ and}$$

$$V_{CE} = 5V - (2.2k\Omega)(4.2mA) = -4.24V.$$

This is not possible so the original assumption of forward active operation was incorrect. The transistor will saturate and the actual collector current will be

$$I_C = \frac{V_{CC} - V_{CES}}{2.2k\Omega} = \frac{5V - 0.1V}{2.2k\Omega} = 2.2mA.$$