# VE320
# Intro to Semiconductor Devices

HOMEWORK 6

November 6, 2020

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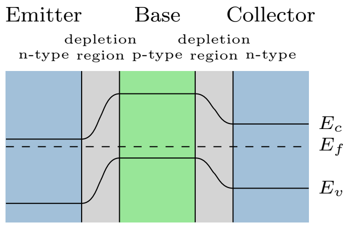
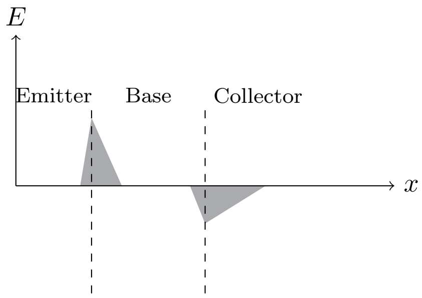
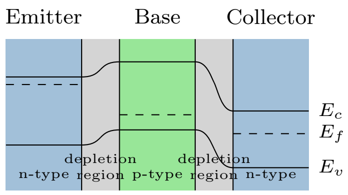
1. (a) Sketch of the energy-band diagram.



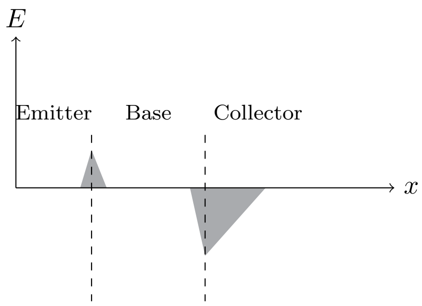

(b) Sketch of the electric field through the device.




(c) Sketch of the energy-band diagram in the forward-active region.




Sketch of the electric field through the device in the forward-active region.




2. (a) The thermal-equilibrium values

$$p_{E0} = \frac{n_i^2}{N_E} = \frac{(1.5 \times 10^{10})^2}{8 \times 10^{17}} = 281.25 \text{ cm}^{-3}.$$

$$n_{B0} = \frac{n_i^2}{N_B} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}.$$

$$p_{C0} = \frac{n_i^2}{N_C} = \frac{(1.5 \times 10^{10})^2}{10^{15}} = 2.25 \times 10^5 \text{ cm}^{-3}.$$

(b) The value of $n_B$ at $x = 0$ for $V_{BE} = 0.64$ V

$$n_B(0) = n_{B0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] = 1.270 \times 10^{15} \text{ cm}^{-3}.$$

The value of $p_E$ at $x' = 0$ for $V_{BE} = 0.64$ V

$$p_E(0) = p_{E0}\left[\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] = 1.587 \times 10^{13} \text{ cm}^{-3}.$$

(c)

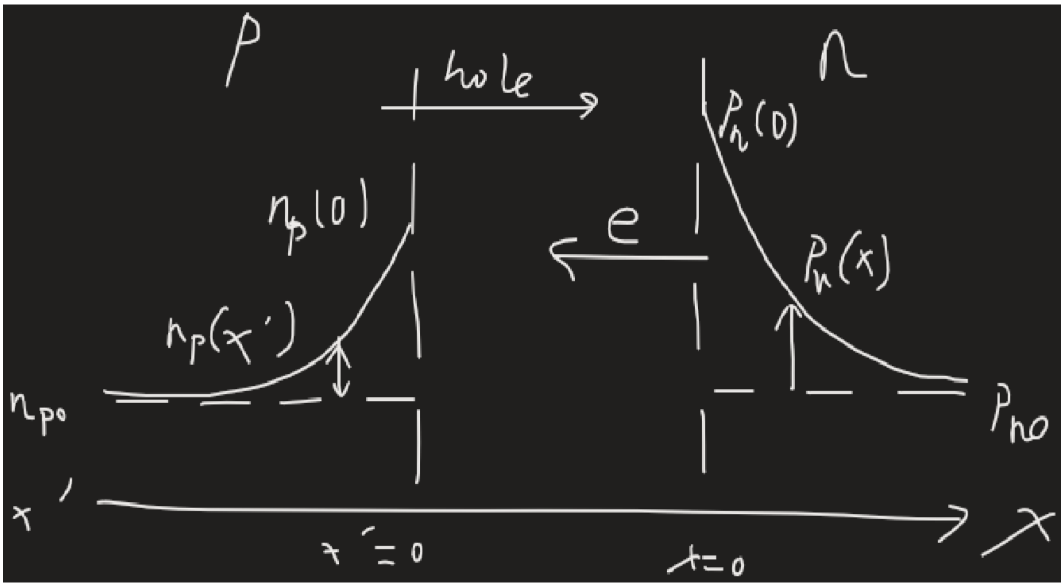



Figure 1: The minority carrier concentrations through the device.

3. (a)

$$\gamma = \frac{I_{nE}}{I_{nE} + I_{pE}} = \frac{500}{500 + 3.5} = 0.9930.$$

$$\alpha_T = \frac{I_{nC}}{I_{nE}} = \frac{0.495}{0.5} = 0.99.$$

$$\delta = \frac{I_{nE} + I_{pE}}{I_{nE} + I_R + I_{pE}} = \frac{500 + 3.5}{500 + 5 + 3.5} = 0.9902.$$

$$\alpha = \frac{I_{nC}}{I_{nE} + I_R + I_{pE}} = \frac{495}{500 + 5 + 3.5} = 0.9735.$$

$$\beta = \frac{\alpha}{1 - \alpha} = 36.67.$$

(b) Given $\beta = 120$,

$$\alpha = \frac{\beta}{1 + \beta} = 0.9917$$

Solving the equation $\gamma = \alpha_T = \delta$, we have

$$\frac{I_{nE}}{I_{nC}} = 0.546.$$

Therefore,

$$I_{nC} = 9.16 \times 10^{-4} \text{ A}.$$
$$I_{pE} = 2.43 \times 10^{-4} \text{ A}.$$
$$I_R = 1.49 \times 10^{-4} \text{ A}.$$

4. Substituting $\frac{n_i^2}{N_E}$ for $p_{E0}$, $\frac{n_i^2}{N_B}$ for $n_{E0}$, $N_E = 100N_B$, $D_E = D_B$, $L_B = L_E$, $x_B = 0.1L_B$, the emitter injection efficiency $\gamma$ is

$$\gamma = \frac{1}{1 + \dfrac{p_{E0}D_E L_B}{n_{B0}D_B L_E} \cdot \dfrac{\tanh\left(x_B/L_B\right)}{\tanh\left(x_E/L_E\right)}} = \frac{1}{1 + \dfrac{0.01\tanh\left(0.1\right)}{\tanh\left(x_E/L_E\right)}}.$$

The graph of the emitter injection efficiency for $0.01L_E \leq x_E \leq 10L_E$ is

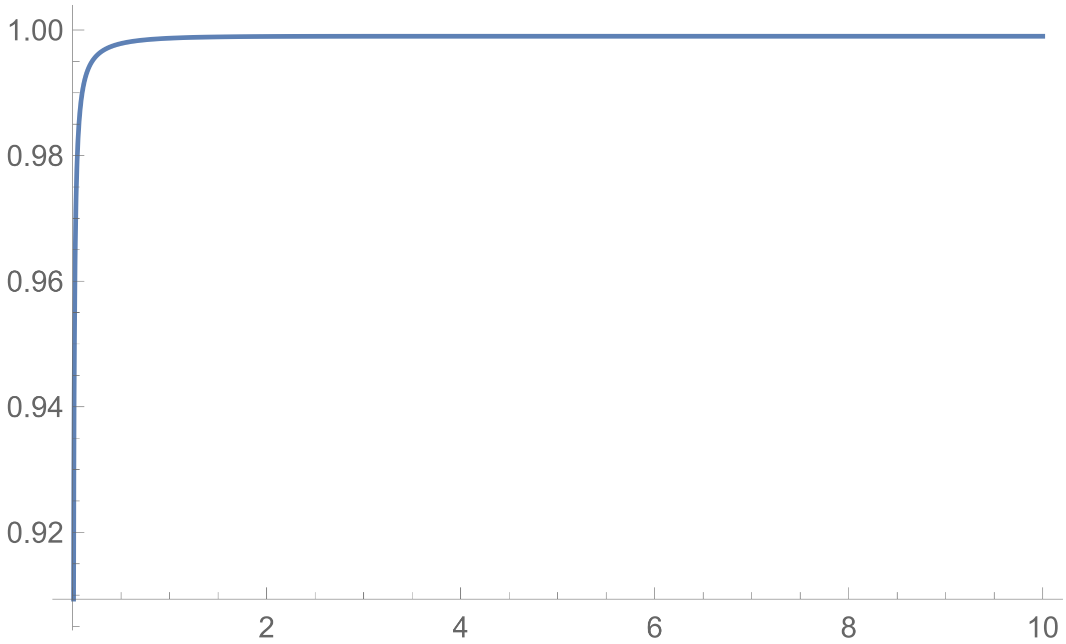



Figure 2: The graph of the emitter injection efficiency for $0.01L_E \leq x_E \leq 10L_E$.

From these results, as the emitter width increases, the emitter injection efficiency increases to a constant, and the common emitter current gain increases.

5. (a) (i) The output resistance

$$r_o = \frac{V_{CE} + V_A}{I_C} = \frac{2 + 120}{1.2 \times 10^{-3}} = 1.017 \times 10^5 \ \Omega.$$

(ii) The output conductance

$$g_o = \frac{I_C}{V_{CE} + V_A} = 9.836 \times 10^{-6} \ \Omega^{-1}.$$

(iii) The collector current

$$I_C = \frac{V_{CE} + V_A}{r_o} = 1.220 \times 10^{-3} \text{ A}.$$

(b) (i) The output resistance

$$r_o = \frac{V_{CE} + V_A}{I_C} = \frac{2 + 160}{0.25 \times 10^{-3}} = 6.48 \times 10^5\ \Omega.$$

(ii) The output conductance

$$g_o = \frac{I_C}{V_{CE} + V_A} = 1.543 \times 10^{-6}\ \Omega^{-1}.$$

(iii) The collector current

$$I_C = \frac{V_{CE} + V_A}{r_o} = 2.531 \times 10^{-4}\ \text{A}.$$

6. (a) (i) Given $x_{BO} \ll L_B$, the excess minority carrier electron concentration in the base can be approximated by

$$\delta n_B(x) \cong \frac{n_{BO}}{x_B} \left\{ \left[ \exp\left(\frac{V_{BE}}{V_t}\right) - 1 \right] (x_B - x) - x \right\}$$

The collector current is

$$|J_C| = eD_B \frac{d[\delta n_B(x)]}{dx} \cong \frac{eD_B n_{BO}}{x_B} \exp\left(\frac{V_{BE}}{V_t}\right)$$

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_B N_C}{n_i^2}\right)$$

$$x_{dB} = \sqrt{\frac{2\epsilon_s (V_{bi} + V_{BC})}{e} \cdot \frac{N_C}{N_B} \cdot \frac{1}{N_C + N_B}}$$

$$n_{BO} = \frac{n_i^2}{N_B} = 1.125 \times 10^4\ \text{cm}^{-3}$$

$$x_B = x_{BO} - x_{dB}$$

Solving the equations, the electron diffusion current density is

$$J_C = 54.71\ \text{A/cm}^2.$$

(ii) The electron diffusion current density is

$$J_C = 59.97\ \text{A/cm}^2.$$

(iii) The electron diffusion current density is

$$J_C = 64.87\ \text{A/cm}^2.$$

(b) We can estimate the Early voltage by

$$\frac{\Delta J_C}{\Delta V_{CE}} = \frac{J_C}{V_{CE} + V_A},$$

where $\Delta J_C$ is the difference between $J_C$ when $V_{CB} = 4$ V and 12 V, $J_C$ is the electron diffusion current density when $V_{CB} = 4$ V, $\Delta V_{CE} = 12 - 4 = 8$ V. Solving the equation, the Early voltage is

$$V_A = 50.11\ \text{V}.$$

7. (a) From the results of 6(a), we have

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_B N_C}{n_i^2}\right)$$

$$x_{dB} = \sqrt{\frac{2\epsilon_s(V_{bi} + V_{BC})}{e} \cdot \frac{N_C}{N_B} \cdot \frac{1}{N_C + N_B}}$$

Solving the equations, when $V_{BC} = 1$ V,

$$x_{dB1} = 1.386 \times 10^{-7} \text{ m},$$

when $V_{BC} = 5$ V,

$$x_{dB1} = 2.574 \times 10^{-7} \text{ m}.$$

The change in neutral base width as $V_{BC}$ changes from 1 to 5 V is

$$\Delta x_B = x_{B1} - x_{B2} = x_{B1} - x_{dB2} = 1.188 \times 10^{-7} \text{ m}.$$

(b) The collector current is

$$I_C = \frac{eD_B p_{BO} A_{BE}}{x_B} \exp\left(\frac{eV_{EB}}{kT}\right),$$

where

$$p_{BO} = \frac{n_i^2}{N_B} = 2.25 \times 10^4 \text{ cm}^{-3}.$$

Thus, when $V_{BC} = 1$ V,

$$I_{C1} = 2.028 \times 10^{-3} \text{ A},$$

when $V_{BC} = 5$ V,

$$I_{C2} = 2.573 \times 10^{-3} \text{ A}.$$

Thus, the corresponding change in collector current is

$$\Delta I_C = I_{C2} - I_{C1} = 5.442 \times 10^{-4} \text{ A}.$$

(c) We can estimate the Early voltage by

$$\frac{\Delta I_C}{\Delta V_{BC}} = \frac{I_C}{V_{EC} + V_A},$$

where $I_C = I_{C1}$ is the collector current when $V_{BC} = 5$ V, $\Delta V_{BC} = 5 - 1 = 4$ V. Solving the equation, the Early voltage is

$$V_A = 13.28 \text{ V}.$$

(d) The output resistance is

$$r_o = \frac{V_{CE} + V_A}{I_C} = 7.350 \times 10^3 \ \Omega.$$