Chapter 5: Bipolar Junction Transistors

5.1. Introduction

5.2. Structure and principle of operation

$$w_E' = w_E - x_{n,BE} \tag{5.2.1}$$

$$w_B' = w_B - x_{p,BE} - x_{p,BC} \tag{5.2.2}$$

$$w_C' = w_C - x_{n,BC} \tag{5.2.3}$$

$$x_{n,BE} = \sqrt{\frac{2e_s(f_{i,BE} - V_{BE})}{q}\frac{N_B}{N_E}\left(\frac{1}{N_B + N_E}\right)} \tag{5.2.4}$$

$$x_{p,BE} = \sqrt{\frac{2e_s(f_{i,BE} - V_{BE})}{q}\frac{N_E}{N_B}\left(\frac{1}{N_B + N_E}\right)} \tag{5.2.5}$$

$$x_{p,BC} = \sqrt{\frac{2e_s(f_{i,BC} - V_{BC})}{q}\frac{N_C}{N_B}\left(\frac{1}{N_B + N_C}\right)} \tag{5.2.6}$$

$$x_{n,BC} = \sqrt{\frac{2e_s(f_{i,BC} - V_{BC})}{q}\frac{N_B}{N_C}\left(\frac{1}{N_B + N_C}\right)} \tag{5.2.7}$$

$$f_{i,BE} = V_t \ln \frac{N_E N_B}{n_i^2} \tag{5.2.8}$$

$$f_{i,BC} = V_t \ln \frac{N_C N_B}{n_i^2} \tag{5.2.9}$$

$$I_E = I_C + I_B \tag{5.2.10}$$

$$I_E = I_{E,n} + I_{E,p} + I_{r,d} \tag{5.2.11}$$

$$I_C = I_{E,n} - I_{r,B} \tag{5.2.12}$$

$$I_B = I_{E,p} + I_{r,B} + I_{r,d} \tag{5.2.13}$$

$$a = \frac{I_C}{I_E} \tag{5.2.14}$$

$$b = \frac{I_C}{I_B} = \frac{a}{1-a} \tag{5.2.15}$$

$$a = a_T g_E d_r \tag{5.2.16}$$

$$g_E = \frac{I_{E.n}}{I_{E,n} + I_{E,p}} \tag{5.2.17}$$

$$a_T = \frac{I_{E,n} - I_{r,B}}{I_E, n} \tag{5.2.18}$$

$$d_r = \frac{I_E - I_{r,d}}{I_E} \tag{5.2.19}$$

5.3. Ideal transistor model

$$I_{E,n} = qn_i^2 A_E \left(\frac{D_{n,B}}{N_B w_B^{'}} \right) \left(\exp(\frac{V_{BE}}{V_t}) - 1 \right) \tag{5.3.1}$$

$$I_{E,p} = qn_i^2 A_E \left(\frac{D_{p,E}}{N_E w_E^{'}} \right) \left(\exp(\frac{V_{BE}}{V_t}) - 1 \right) \tag{5.3.2}$$

$$\Delta Q_{n,B} = q A_E \int_{x_{p,E}}^{w_B - x_{p,C}} n_p(x) - n_{p0} \, dx \tag{5.3.3}$$

$$\Delta Q_{n,B} = q A_E \frac{n_i^2}{N_B} \left(\exp(\frac{V_{BE}}{V_t}) - 1 \right) \frac{w_B^{'}}{2} \tag{5.3.4}$$

$$I_{E,n} = \frac{\Delta Q_{n,B}}{t_r} \tag{5.3.5}$$

$$t_r = \frac{w_B^{'\,2}}{2D_{n,B}} \tag{5.3.6}$$

$$\frac{\partial n_p(x)}{\partial t} = \frac{1}{q} \frac{\partial J_n(x)}{\partial x} - \frac{n_p(x) - n_{p0}}{t_n} \tag{5.3.7}$$

$$I_{r,B} = A_E \int_{x_{p,BE}}^{w_B - x_{p,BC}} \frac{\partial J_n(x)}{\partial x} dx = qA_E \int_{x_{p,BE}}^{w_B - x_{p,BC}} \frac{n_p(x) - n_{p0}}{t_n} dx \tag{5.3.8}$$

$$I_{r,B} = \frac{\Delta Q_{n,B}}{t_n} \tag{5.3.9}$$

$$g_E = \frac{1}{1 + \dfrac{D_{p,E} N_B w_B^{'}}{D_{n,B} N_E w_E^{'}}} \tag{5.3.10}$$

$$b \cong \frac{D_{n,B} N_E w_E^{'}}{D_{p,E} N_B w_B^{'}}, \quad \text{if} \quad a \cong g_E \tag{5.3.11}$$

$$a_T = 1 - \frac{t_r}{t_n} = 1 - \frac{w_B^{'\,2}}{2 D_{n,B} t_n} \tag{5.3.12}$$

$$a_T = 1 - \frac{1}{2} \left(\frac{w_B^{'}}{L_n}\right)^2 \tag{5.3.13}$$

5.3.1. General bias modes of a bipolar transistor

$$I_E = I_F - a_R I_R \tag{5.3.14}$$

$$I_B = (1 - a_F) I_F + (1 - a_R) I_R \tag{5.3.15}$$

$$I_C = -I_R + a_F I_F \tag{5.3.16}$$

$$I_{E,s} a_F = I_{C,s} a_R \tag{5.3.17}$$

$$I_F(V_{BE})\, a_F = I_R(V_{BC} = V_{BE})\, a_R \tag{5.3.18}$$

$$V_{CE,sat} = V_{BE} - V_{BC} = V_t \ln\left\{\frac{I_F}{I_R} \frac{I_{C,s}}{I_{E,s}}\right\} \tag{5.3.19}$$

$$V_{CE,sat} = V_t \ln\left\{\frac{1 + \dfrac{I_C}{I_B}(1 - a_R)}{a_R\left[1 - \dfrac{I_C}{I_B} \dfrac{(1 - a_F)}{a_F}\right]}\right\} \tag{5.3.20}$$

5.4. Non-ideal effects

$$\frac{dI_C}{dV_{CE}} \cong -\frac{dI_C}{dV_{BC}} = \frac{I_C}{w_B^{'}} \frac{dw_B^{'}}{dV_{BC}} \tag{5.4.1}$$

$$\frac{dI_C}{dV_{CE}} \cong \frac{I_C}{|V_A|} \tag{5.4.2}$$

$$|V_A| = \frac{Q_{p,B}}{C_{j,BC}} = \frac{qA_C N_B w_B^{'}}{\dfrac{e_s A_C}{x_{p,BC} + x_{n,BC}}} \tag{5.4.3}$$

$$n = \frac{1}{V_t \dfrac{d \ln I_C}{dV_{BE}}} \cong 1 + \frac{V_t}{Q_{p,B}} C_{j,BE} \tag{5.4.4}$$