Chapter 7: MOS Field Effect Transistors

7.3. MOSFET analysis

$$I_D = -\frac{Q_{inv} WL}{t_r} \tag{7.3.1}$$

$$t_r = \frac{L}{v} \tag{7.3.2}$$

$$v = mE = m\frac{V_{DS}}{L} \tag{7.3.3}$$

$$I_D = -m \cdot Q_{inv} \cdot \frac{W}{L} \cdot V_{DS} \tag{7.3.4}$$

$$Q_{inv} = -C_{ox}(V_{GS} - V_T), \text{ for } V_{GS} > V_T \tag{7.3.5}$$

$$Q_{inv} = 0, \text{ for } V_{GS} \le V_T$$

$$I_D = mC_{ox}\frac{W}{L}(V_{GS} - V_T)V_{DS}, \text{ for } |V_{DS}| << (V_{GS} - V_T) \tag{7.3.6}$$

$$I_D = mC_{ox}\frac{W}{dy}(V_G - V_S - V_C - V_T)dV_C \tag{7.3.7}$$

$$\int_0^L I_D\, dy = mC_{ox} W \int_0^{V_{DS}} (V_G - V_S - V_C - V_T)dV_C \tag{7.3.8}$$

$$I_D = mC_{ox}\frac{W}{L}[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}], \quad \text{for } V_{DS} < V_{GS} - V_T \tag{7.3.9}$$

$$I_{D,sat} = mC_{ox}\frac{W}{L}\frac{(V_{GS} - V_T)^2}{2}, \quad \text{for } V_{DS} > V_{GS} - V_T \tag{7.3.10}$$

$$I_D = 0, \quad \text{for } V_{GS} < V_T \tag{7.3.11}$$

$$g_m \overset{\Delta}{=} \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}} \tag{7.3.12}$$

$$g_{m,quad} = mC_{ox}\frac{W}{L}V_{DS} \tag{7.3.13}$$

$$g_{m,sat} = mC_{ox}\frac{W}{L}(V_{GS} - V_T) \tag{7.3.14}$$

$$g_d \triangleq \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_{GS}} \tag{7.3.15}$$

$$g_{d,quad} = \mu C_{ox}\frac{W}{L}(V_{GS} - V_T - V_{DS}) \tag{7.3.16}$$

$$g_{d,sat} = 0 \tag{7.3.17}$$

$$I_{D,sat} = \mu C_{ox}\frac{W}{L}\frac{(V_{GS}-V_T)^2}{2}(1+\lambda V_{DS}), \quad \text{for } V_{DS} > V_{GS} - V_T \tag{7.3.18}$$

$$Q_{inv} = -C_{ox}(V_{GS} - V_T), \text{ for } V_{GS} > V_T \tag{7.3.19}$$

$$V_T = V_{FB} + V_C + 2\phi_F + \frac{\sqrt{2\varepsilon_s q N_a (2\phi_F + V_{SB} + V_C)}}{C_{ox}} \tag{7.3.20}$$

$$I_D = \mu_n C_{ox}\frac{W}{dy}(V_{GS} - V_{FB} - 2\phi_F - V_C - \frac{\sqrt{2\varepsilon_s q N_a (2\phi_F + V_{SB} + V_C)}}{C_{ox}})dV_C \tag{7.3.21}$$

$$\int_0^L I_D\,dy = \mu_n C_{ox} W \int_0^{V_{DS}} (V_{GS} - V_{FB} - 2\phi_F - V_C)dV_C - \mu_n W \int_0^{V_{DS}} \sqrt{2\varepsilon_s q N_a (2\phi_F + V_{SB} + V_C)}\,dV_C \tag{7.3.22}$$

$$I_D = \frac{\mu_n C_{ox} W}{L}(V_{GS} - V_{FB} - 2\phi_F - \frac{V_{DS}}{2})V_{DS} - \frac{2}{3}\mu_n \frac{W}{L}\sqrt{2\varepsilon_s q N_a}((2\phi_F + V_{DB})^{3/2} - (2\phi_F + V_{SB})^{3/2}) \tag{7.3.23}$$

$$V_{DS,sat} = V_{GS} - V_{FB} - 2\phi_F - \frac{qN_a\varepsilon_s}{C_{ox}^2}\{\sqrt{1 + 2\frac{C_{ox}^2}{qN_a\varepsilon_s}(V_{GB} - V_{FB})} - 1\} \tag{7.3.24}$$

$$g_{m,sat} = \mu_n C_{ox}\frac{W}{L}[V_{GS} - V_{FB} - 2\phi_F - \frac{qN_a\varepsilon_s}{C_{ox}^2}\{\sqrt{1 + 2\frac{C_{ox}^2}{qN_a\varepsilon_s}(V_{GB} - V_{FB})} - 1\}] \tag{7.3.25}$$

$$g_{m,sat} = \mu_n^* C_{ox}\frac{W}{L}(V_{GS} - V_T) \tag{7.3.26}$$

$$m_n^* = m_n\left(1-\frac{1}{\sqrt{1+\frac{2(2f_F+V_{SB})C_{ox}^2}{qN_a e_s}}}\right) \tag{7.3.27}$$

7.4. Threshold voltage

$$V_T = V_{FB} + 2f_F + \frac{\sqrt{2e_s qN_a(2f_F+V_{SB})}}{C_{ox}} \tag{7.4.1}$$

$$V_{FB} = \Phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}}\int_0^{t_{ox}} \frac{x}{x_{ox}} r_{ox}(x)dx \tag{7.4.2}$$

$$\Phi_{MS} = \Phi_M - \Phi_S = \Phi_M - (c + \frac{E_g}{2q} + f_F) \tag{7.4.3}$$

$$f_F = V_t \ln\frac{N_a}{n_i}, \text{p - substrate} \tag{7.4.4}$$

$$V_T = V_{FB} - |2f_F| - \frac{\sqrt{2e_s qN_d(|2f_F| - V_{SB})}}{C_{ox}} \tag{7.4.5}$$

$$V_{FB} = \Phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}}\int_0^{t_{ox}} \frac{x}{x_{ox}} r_{ox}(x)dx \tag{7.4.6}$$

$$\Phi_{MS} = \Phi_M - \Phi_S = \Phi_M - (c + \frac{E_g}{2q} - |f_F|) \tag{7.4.7}$$

$$|f_F| = V_t \ln\frac{N_d}{n_i}, \text{n - substrate} \tag{7.4.8}$$

$$V_T = V_{FB} + 2f_F + \frac{\sqrt{2e_s qN_a(2f_F+V_{SB})}}{C_{ox}} \tag{7.4.9}$$

$$\Delta V_T = g\,(\sqrt{(2f_F+V_{SB})} - \sqrt{2f_F}) \tag{7.4.10}$$

$$g = \frac{\sqrt{2e_s qN_a}}{C_{ox}} \tag{7.4.11}$$

7.5. MOSFET SPICE MODEL

7.6. MOSFET Circuits and Technology

7.7. Advanced MOSFET issues

$$I_D \propto \exp\left(\frac{V_G - V_T}{nV_t}\right) \tag{7.7.1}$$

$$n = 1 + \frac{1}{2C_{ox}}\sqrt{\frac{qe_s N_a}{f_F}} \tag{7.7.2}$$

$$Q_d \propto \exp\left(\frac{f_s}{V_t}\right) \tag{7.7.3}$$

$$V_G = V_{FB} + f_s + V_{ox} = V_{FB} + f_s + \frac{\sqrt{2qe_s f_s}}{C_{ox}} \tag{7.7.4}$$

$$\frac{dV_G}{df_s} = 1 + \frac{1}{2C_{ox}}\sqrt{\frac{2qe_s}{f_s}} \cong 1 + \frac{1}{2C_{ox}}\sqrt{\frac{qe_s}{2f_F}} = n \tag{7.7.5}$$

$$I_D \propto Q_d \propto \exp\left(\frac{f_s}{V_t}\right) \propto \exp\left(\frac{V_G}{nV_t}\right) \tag{7.7.6}$$

$$m_{surface} \propto E^{-1/3} \tag{7.7.7}$$