3. A silicon p-channel (n-substrate) MOS capacitor with a polysilicon gate heavily doped with boron ($E_f = E_v$) has a substrate doping of $N_d = 2 \times 10^{18}\text{cm}^{-3}$ and an oxide thickness of $x_{ox} = 2\,\text{nm}$. There are no significant interface charges. The device is biased such that the voltage dropped across the oxide is 0.5 V (more positive toward gate).

(a) Calculate the charge in the semiconductor and on the gate. What mode is the device operating in? (10)

$$V_{ox} = \frac{Q_g}{C_{ox}'} = -\frac{Q_s}{C_{ox}} \quad \text{(no oxide charges)}$$

$$C_{ox}' = \frac{K_{ox}\epsilon_0}{X_{ox}} = \frac{3.9 \times 8.854\times10^{-14}\,F/cm}{2\times10^{-7}\,cm} = 1.73\times10^{-6}\,F/cm^2$$

$$Q_g = 0.5V * 1.73\times10^{-6}\,F/cm^2 = 8.6\times10^{-7}\,C/cm^2$$

$$Q_s = -Q_g = -8.6\times10^{-7}\,C/cm^2 < 0 \Rightarrow \text{accumulation of electrons in n-substrate}$$

(b) What is the applied voltage between the gate and substrate? (12)

$$V_{GB} = V_{FB} + V_S + \Delta V_{ox} = \phi_{MS} + V_s + V_{ox}$$

$$\phi_M = \chi_s + E_g, \quad \phi_S = \chi_s + \frac{kT}{q}\ln\frac{N_c}{N_d} = \chi_s + 0.07V$$

$$\phi_{MS} = 1.12 - 0.07 = 1.05V$$

$$V_S \cong 0 \text{ in accumulation}$$

$$V_{GB} = 1.05 + 0.5 = 1.55V$$

4. A silicon n-channel MOS transistor has an oxide thickness of 2 nm, uniform substrate doping of $Na = 2\times 10^{18}\text{cm}^{-3}$ and $W = 300\text{nm}$ and $L = 100\text{nm}$. $V_T = 0.4\,\text{V}$ with $V_S = V_B = 0\,\text{V}$. Assume $\mu_n' = 150\,\text{cm}^2/\text{Vs}$ in the inversion layer.

(a) If the gate metal work function is 4.0V, what must the oxide interface charges be (assume no charges in bulk of oxide)? (12)

$V_{FB} = \phi_{MS} - \frac{Q_{ss}'}{C_{ox}'}$

$V_T = V_{FB} - 2\phi_F - \frac{Q_{d,max}'}{C_{ox}'}$

$0.4V = \phi_{MS} - \frac{Q_{ss}'}{C_{ox}'} + 0.99 + \frac{8.14\times10^{-7} C/cm^2}{1.73\times10^{-6} F/cm^2}$

$\phi_F = \phi_p = -\frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right) = -0.495$

$\phi_s = \chi_s + E_g - \frac{kT}{q}\ln\left(\frac{N_v}{Na}\right) = 4.05 + 1.12 - 0.07$

$= -1.1 - \frac{Q_{ss}'}{C_{ox}'} + 0.99 + \frac{8.14}{17.3}$

$Q_{d,max} = -\sqrt{2qK_s\epsilon_0 N_d\,|-2\phi_F|}$

$Q_{ss}' = C_{ox}'\left[0.99 - 1.1 + 0.47 - 0.4\right]$

$= -\left[2(1.6\times10^{-19}C)(11.8\times8.854\times10^{-14}\frac{F}{cm})(2\times10^{18}cm^{-3})0.9\ldots\right]$

$= -6.9\times10^{-8} C/cm^2$

$= -8.14\times10^{-7} C/cm^2$

(b) Calculate the change in threshold voltage with the change in channel to substrate bias (δ) for $V_{SB} = 0$. (12)

$\delta = \frac{C_d'}{C_{ox}'}$

$C_d' = \frac{K_s\epsilon_0}{X_d}$

$X_d = \frac{-Q_{d,max}}{q\,Na} = \frac{8.14\times10^{-7} C/cm^2}{(1.6\times10^{-19}C)(2\times10^{18}cm^{-3})}$

$= \frac{(11.8)(8.854\times10^{-14}\frac{F}{cm})}{2.54\times10^{-6}cm}$

$= 2.54\times10^{-6} cm$

$= \frac{4.1\times10^{-7}\frac{F}{cm^2}}{1.73\times10^{-6} F/cm^2}$

$= 4.1\times10^{-7} F/cm^2$

$= 0.24$

(c) If $V_S = V_B = 0V$ and $V_G = 2V$, what drain voltage would bring the transistor to the edge of saturation. (Use full or linearized model). (8)

$V_{DS}^{sat} = \frac{V_{GS} - V_T}{1+\delta} = \frac{2-0.4}{1.24} = 1.29V$

(d) For $V_D = 2V$ (and $V_S = V_B = 0V$, $V_G = 2.0V$), determine the operating mode and calculate the drain current. Include channel length modulation if appropriate. (14)

$V_{DS} = 2V > V_{DS}^{sat} = 1.29V$

$L = L - \Delta L = 8\times10^{-6}\ cm$

$\Delta L = \left[\frac{2K_s\epsilon_0(V_{DS} - V_{DS}^{sat})}{qN_a}\right]^{1/2} = \left[\frac{2(11.8)(8.854\times10^{-14}\frac{F}{cm})(0.61V)}{(1.6\times10^{-19}C)(2\times10^{18}cm^{-3})}\right]^{1/2}$

$= 2.0\times10^{-6}\ cm$

$I_{DS}^{sat} = \mu_n' \frac{W}{L} C_{ox}' \frac{(V_{DS}^{sat} - V_T)^2}{2*1+\delta}$

$= (150\frac{cm^2}{V\cdot s})(\frac{300}{80})(1.73\times10^{-6}\frac{F}{cm^2}) * \frac{(2-0.4)^2}{2*1.24}$

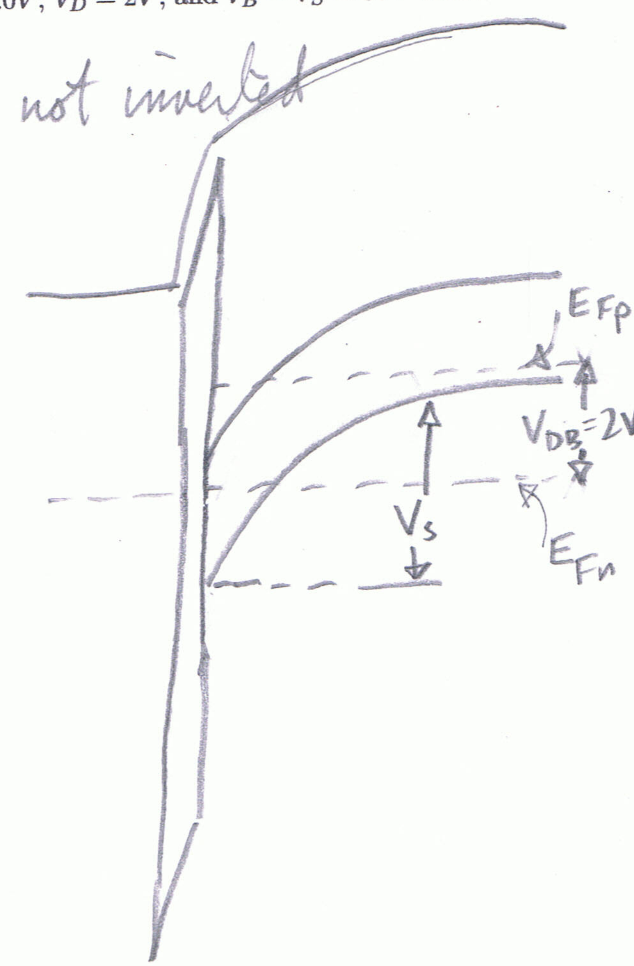
$= 1.0\times10^{-3}A = 1\ mA$

$\mathcal{E}_{eff} = \frac{V_{GS}+V_T+0.2}{6t_{ox}} = 2.2\times10^6\frac{V}{cm}$

$\mu_n' \cong 90\ cm^2/V\cdot s$ from plot, but use 150

(e) Sketch the band diagram in channel near drain if $V_G = 2.0V$, $V_D = 2V$, and $V_B = V_S = 0V$. What is the voltage dropped across the semiconductor? (12)

$V_{DS} > V_{DS}^{sat}$, so drain end of channel not inverted



$V_{GB} = V_{FB} + V_s + \frac{\sqrt{2K_s\epsilon_0 qN_aV_s}}{C_{ox}'}$

$= \phi_{MS} - \frac{Q_{ss}'}{C_{ox}'} + V_s + 0.47\sqrt{V_s}$

$2 = -1.1 + 0.4 + V_s + 0.47\sqrt{V_s}$

$x = \sqrt{V_s}$

$x^2 + 0.47x - 3.06 = 0$

$x = \frac{-0.47 \pm \sqrt{(0.47)^2 + 4(3.06)}}{2}$

$= 1.53$

$V_s = 2.34\ V$