FinalA - EE 5340/4329 (print last name) key (print first name)
Tuesday, December 4, 2001, 9:30 AM
80 minutes allowed (last four digits of your student #) (e-mail if new)

Instructions:

1. Do your own work.
2. You may use either a legal copy of the text or ONE sheet of hand-written notes. You may NOT pass a book or note sheet to another student. You may NOT use class notes. Do not use previously solved problems.
3. Calculator allowed. You may NOT share a calculator with another student.
4. Explicitly state definitions and assumptions that you use.
5. Where possible, calculate parameters rather than read them from a graph.
6. Do all work in the spaces provided on this exam paper. If you write on the back of a sheet, make the notation "PTO" in your solution in order to assure that material written on the back of the page is evaluated for a grade.
7. Show all calculations, making numerical substitutions and giving numerical results where possible.
8. Write answers in space given.
9. Unless stated otherwise, $T = 300K$, $V_t = 25.852$ mV
10. Unless otherwise stated, the material is silicon with $n_i = 1.07E10\ cm^{-3}$, $N_c = 2.84E19\ cm^{-3}$, $N_v = 3.08E19\ cm^{-3}$, $q\chi_{Si} = 4.05$ eV, and $E_{g,Si} = 1.125$ eV.
11. For the work function of n+ poly silicon, use $\phi_{n+} = \chi_{si} = 4.05$ V, and for the work function of p+ poly silicon, use $\phi_{p+} = \chi_{Si} + E_{g,Si}/q = 5.175$ V.
12. For minority carriers in silicon, use the relationship $\tau_{min} = [45E\text{-}6\ sec]\div[1+7.7E\text{-}18*N_i+4.5E\text{-}36*N_i^2]$ (where N_i = the total impurity concentration) for minority carrier lifetime (either electrons or holes).
13. For holes in silicon, assume $\mu_p = \{418.3\div[1+(N_i\div1.6E17)^{0.7}]\}+49.7$, in $cm^2/V\text{-}sec$ (where N_i = the total impurity concentration in n- or p-type material whether compensated or uncompensated).
14. For electrons in silicon, assume $\mu_n = \{1268\div[1+(N_i\div1.3E17)^{0.91}]\}+92$, in $cm^2/V\text{-}sec$ (where N_i = the total impurity concentration in n- or p-type material whether compensated or uncompensated).
15. Metal gate work functions should be assumed to be $\phi_{Au} = 4.75$ V, $\phi_{Al} = 4.1$V.
16. The electron affinity of SiO_2 is $\chi_{SiO2} = 0.95$ V.
17. Each part is worth [x] points, as given in the problem.

1. An nmos capacitor structure is to be made on $N_a = 7E14\ cm^{-3}$ silicon material. The gate is n+ poly silicon and the gate oxide is 200 nm thick.

a. What is the ϕ_{ms} value for this structure?

$\Phi_m = 4.05$ $\quad\quad$ $\Phi_s = \chi_{si} + E_g + (E_v - E_f)$ $\quad\quad$ $E_v - E_f = -\frac{kT}{q} \ln\left(\frac{P}{N_v}\right)$

$\Phi_{ms} = \Phi_m - \Phi_s = 4.05 - 4.05 - 1.125 + 0.276 = -0.85V$ $\quad\quad$ $= -0.025852 \ln\left(\frac{7\times10^{14}}{3.08\times10^{19}}\right)$

$= -0.276\ V$

Answer a. [6] ϕ_{ms} = -0.85 V.

b. Calculate the oxide capacitance per unit area.

$$C_{ox}' = \frac{\varepsilon_{ox}}{d} = \frac{3.9\times8.85\times10^{-14}}{200\times10^{-7}} = 1.73\times10^{-8}$$

Answer b. [6] C'_{Ox} = $1.73\times10^{-8}\ Fd/cm^2$.

c. Calculate the flat band voltage for this structure.

$$V_{FB} = \Phi_{ms} = -0.85\ V$$

Answer c. [6] V_{FB} = -0.85 V.

d. Calculate the capacitance per unit area at the flat band condition.

$$L_D = \sqrt{\frac{\varepsilon V_t}{q N_a}} = \sqrt{\frac{11.7\times8.85\times10^{-14}\times0.025852}{1.6\times10^{-19}\times7\times10^{14}}} = 1.55\times10^{-5}\ cm$$

$$C_{FB}' = \frac{1}{\frac{t_{ox}}{\varepsilon_{ox}} + \frac{L_D}{\varepsilon_{si}}} = \frac{1}{\frac{200\times10^{-7}}{3.9\times8.85\times10^{-14}} + \frac{1.55\times10^{-5}}{11.7\times8.85\times10^{-14}}} = 1.37\times10^{-8}\ Fd/cm^2$$

Answer d. [6] C'_{FB} = $1.37\times10^{-8}\ Fd/cm^2$.

e. Calculate the capacitance per unit area for deep accumulation of majority carriers.

$$C_{accum}' = C_{ox}'$$

Answer e. [6] C'_{accum} = $1.73\times10^{-8}\ Fd/cm^2$.

2. A pmos structure is to be made on $N_d = 1E15\ cm^{-3}$ silicon material. The gate is aluminum and the gate oxide is 100 nm thick. A surface charge density of $Q'_{ss} = +q*1E11\ cm^{-2}$ is at the Si/SiO$_2$ interface.

a. What is the ϕ_{ms} for this structure?

$$\phi_s = \chi_{si} + (E_c - E_f)$$

$$E_c - E_f = \frac{KT}{q} \ln\left(\frac{N_c}{n}\right) = 0.025852 \times \ln\left(\frac{2.84\times10^{19}}{1\times10^{15}}\right) = 0.265\ V$$

$$\phi_{ms} = \phi_m - \phi_s = 4.1 - 4.05 - 0.265 = -0.215\ V$$

Answer a. [6] ϕ_{ms} = $-0.215\ V$.

b. Calculate the oxide capacitance per unit area.

$$C'_{ox} = \frac{\varepsilon_{ox}}{d} = \frac{3.9\times8.85\times10^{-14}}{100\times10^{-7}} = 3.45\times10^{-8}$$

Answer b. [6] C'_{Ox} = $3.45\times10^{-8}\ Fd/cm^2$.

c. Calculate the flat band voltage for this structure.

$$V^0_{FB} = \phi_{ms} = -0.215\ V.$$

$$V_{FB} = V^0_{FB} - \frac{Q'_{ss}}{C'_{ox}} = -0.215 - \frac{1.6\times10^{-19}\times1\times10^{11}}{3.45\times10^{-8}} = -0.679\ V$$

Answer c. [6] V_{FB} = $-0.679\ V$.

d. Calculate the capacitance per unit area at the onset of strong inversion and at high frequency (i.e. the minority carrier concentration is not significantly affected by the thermal generation/recombination processes).

$$\phi_b = \frac{KT}{q} \ln\left(\frac{N_D}{n_i}\right) = 0.025852 \times \ln\left(\frac{1\times10^{15}}{1.07\times10^{10}}\right) = 0.296$$

$$X_{dmax} = \sqrt{\frac{2\varepsilon_{si}\, 2\phi_b}{q N_D}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times2\times0.296}{1.6\times10^{-19}\times1\times10^{15}}} = 8.75\times10^{-5}\ cm$$

$$C'_{min} = \frac{1}{\frac{1}{C'_{ox}} + \frac{X_{dmax}}{\varepsilon_{si}}} = \frac{1}{\frac{1}{3.45\times10^{-8}} + \frac{8.75\times10^{-5}}{11.7\times8.85\times10^{-14}}} = 8.8\times10^{-9}$$

Answer d. [6] C'_{min} = $8.8\ nF/cm^2$.

3. An nmos structure is made on N_a = 1E15 cm^{-3} silicon material. The gate is n+ poly silicon and the gate oxide is 200 nm thick. A surface charge density of Q'_{ss} = +q*1E11 cm^{-2} is at the Si/SiO$_2$ interface. There are contacts at the gate, source, drain and bulk.

a. What is the V_{FB} for this structure?

$$C_{ox}' = \frac{\varepsilon_{ox}}{d} = \frac{3.9 \times 8.85 \times 10^{-14}}{200 \times 10^{-7}} = 1.73 \times 10^{-8}$$

$$\phi_s = \chi_{si} + E_g + (E_v - E_f)$$

$$= 4.05 + 1.125 - 0.267 = 4.908$$

$$V_{FB}^0 = \phi_m - \phi_s = 4.05 - 4.908 = -0.85$$

$$E_v - E_f = -\frac{kT}{q} \ln\left(\frac{P}{N_V}\right) = -0.025852 \times \ln\left(\frac{1 \times 10^{15}}{3.08 \times 10^{19}}\right)$$

$$= 0.267$$

$$V_{FB} = V_{FB}^0 - \frac{Q_{ss}'}{C_{ox}'} = -0.858 - \frac{1.6 \times 10^{-19} \times 1 \times 10^{11}}{1.73 \times 10^{-8}}$$

$$= -1.78$$

Answer a. [6] V_{FB} = -1.78 V .

b. Calculate the total depletion charge per unit area in the silicon at the onset of strong inversion when $v_D = v_S = v_B = 0$.

$$\phi_b = \frac{kT}{q} \ln\left(\frac{n_i}{N_a}\right)$$

$$= 0.025852 \times \ln\left(\frac{1.07 \times 10^{10}}{1 \times 10^{15}}\right)$$

$$= -0.296$$

$$X_{dmax} = \sqrt{\frac{2\varepsilon_{si}\, 2|\phi_b|}{q N_a}} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times 2 \times 0.296}{1.6 \times 10^{-19} \times 1 \times 10^{15}}} = 8.75 \times 10^{-5}\ \text{cm}$$

$$Q_{depl}' = q N_a X_{dmax}$$

$$= 1.6 \times 10^{-19} \times 1 \times 10^{15} \times 8.75 \times 10^{-5}$$

$$= 1.4 \times 10^{-8}$$

Answer b. [6] $Q'_{depl,OSI}$ = 1.4×10^{-8} coul/cm^2.

c. Calculate the threshold voltage when $v_D = v_S = v_B = 0$.

$$V_{Th} = V_{FB} + 2|\phi_b| + \frac{\sqrt{2 q \varepsilon_{si} N_a 2|\phi_b|}}{C_{ox}'} = V_{FB} + 2|\phi_b| + \frac{Q_{depl,osi}}{C_{ox}'}$$

$$= -1.78 + 2 \times 0.296 + \frac{1.6 \times 10^{-8}}{1.73 \times 10^{-8}} = -0.378$$

Answer c. [6] V_{Th} = -0.378 V .

e. Calculate the threshold voltage when $v_D = v_S = 0$, and v_B = -5V.

$$\Delta V_{Th} = \frac{\sqrt{2 q \varepsilon_{si} N_a}}{C_{ox}'}\left(\sqrt{2|\phi_b| + V_{SB}} - \sqrt{2|\phi_b|}\right) = \frac{\sqrt{2 \times 1.6 \times 10^{-19} \times 11.7 \times 8.85 \times 10^{-14} \times 1 \times 10^{15}}}{1.73 \times 10^{-8}}$$

$$\times\left(\sqrt{2 \times 0.296 + 5} - \sqrt{2 \times 0.296}\right)$$

$$= 1.68$$

$$V_{Th} = V_{Th}^0 - \Delta V_T$$

$$= -0.378 - 1.68$$

$$= -2.06$$

Answer d. [7] V_{Th} = -2.06 V .

4. Considering the same nmos structure made on N_a = 1E15 cm^{-3} silicon material. The gate is n+ poly silicon and the gate oxide is 200 nm thick. A surface charge density of Q'_{ss} = +q*1E11 cm^{-2} is at the Si/SiO$_2$ interface. There are contacts at the gate, source, drain and bulk. The ratio W/L = 100.

a. In the strong inversion approximation, what is the inversion charge per unit area when $v_G = V_{Th} + 1V$ and $v_D = v_S = v_B = 0$.

$$Q_n' = -C_{ox}'(V_G - V_{Th}) = -1.73\times10^{-8} \times 1 = -1.73\times10^{-8}$$

Answer a. [7] Q'_n = -1.73×10^{-8} coul/cm^2

b. Further, assume that in a FET made using this structure, the channel carrier mobility is one-half of the mobility that would be observed in the bulk. Find the channel carrier mobility.

NMOS $\quad N_a = 1\times10^{15}$

$$\mu_n = \frac{1268}{1+\left(\frac{1\times10^{15}}{1.3\times10^{17}}\right)^{0.91}} + 92 = 1345$$

$$\mu_{n,channel} = \frac{\mu_{n,bulk}}{2} = \frac{1345}{2} = 672.5$$

Answer b. [6] $\mu_{n,channel}$ = 672.5 cm^2/V·S.

c. Furthermore, solve for the nmos FET drain current when $v_G = V_{Th} + 1V$ and $v_D - v_S = v_{DS,sat}$. Assume the uniform channel charge model that gives square-law behavior.

$V_G > V_{Th}$ $\quad V_{DS} = V_{DS,sat}$
$\quad = V_G - V_{Th}$

NMOS is operated at the boundary of ohmic and saturation regions.

ohmic

$$I_D = \frac{W}{L}\mu_n C_{ox}'\left[(V_G - V_T) - \frac{V_{DS}}{2}\right]\cdot V_{DS}$$

or.

Sat

$$I_D = \frac{W}{2L}\mu_n C_{ox}'(V_G - V_T)^2 = 50 \times 672.5 \times 1.73\times10^{-8} \times 1 = 5.82\times10^{-4}\text{ A}.$$

Answer c. [8] i_D= 0.582 mA.