Test 3 - EE 5340/4329 (print last name)____________________ (print first name) Key
Tu, December 12, 2000
90 minutes allowed (student #)______-____-______ (e-mail)____________________

Instructions: Do your own work. Open book (including class handouts), calculator allowed, no notes. Each part is worth [x] points. **Explicitly state definitions and assumptions that you use. Where possible, calculate parameters rather than read them from a graph.** Do all work on this paper. Show all calculations, making numerical substitutions and giving numerical results where possible. Write answers in space given. Unless stated otherwise, T = 300K and V_t = 25.852 mV. **Note: When instructed to calculate, you should proceed from the appropriate formula and compute the desired value and not read it from a graph.**

1 A boron doped (Na = 3E14/cm^3) is to be used to fabricate an MOS capacitor. The only contacts are to the gate and the bulk or substrate (V_B = 0). The oxide thickness is 350E-7 cm. The gate material is n+ polysilicon.
a Calculate the gate workfunction.

n^+ poly-Si : $\phi_m = \chi_{Si} = 4.05$

a [4] ϕ_m = 4.05 V . b Next, calculate the p substrate workfunction.

$q\Phi_s = q\chi_{Si} + E_g - (E_f - E_v)$

$= 4.05 + 1.125 - 0.298 = 4.877$

$E_f - E_v = \frac{kT}{q}\ln\left(\frac{N_v}{N_a}\right)$

$= 0.025852 \times \ln\left(\frac{3.08\times10^{19}}{3\times10^{14}}\right)$

$= 0.298\text{ V}$

b [4] ϕ_s = 4.877 V . c Next, calculate the Debye length for carrier concentration transition at the oxide-silicon interface.

$$L_D = \sqrt{\frac{\varepsilon V_t}{q N_a}} = \sqrt{\frac{11.7\times8.85\times10^{-14}\times0.025852}{1.6\times10^{-19}\times3\times10^{14}}} = 2.36\times10^{-5}\text{ cm}$$

c [5] L_D = 23.6 μm . d Next, calculate the oxide capacitance per cm^2.

$$C'_{ox} = \frac{\varepsilon_{ox}}{d} = \frac{3.9\times8.85\times10^{-14}}{350\times10^{-7}} = 9.86\text{ nF/cm}^2$$

d [4] C'_{Ox} = 9.86 nF/cm^2 . e Next, calculate the flat-band capacitance per cm^2.

$$C'_{dif}(FB) = \frac{1}{\frac{1}{C'_{ox}} + \frac{L_D}{\varepsilon_{Si}}} = \frac{1}{\frac{1}{9.86\times10^{-9}} + \frac{2.36\times10^{-5}}{11.7\times8.85\times10^{-14}}} = 8.05\times10^{-9}$$

e [4] C'_{FB} = 8.05 nF/cm^2 .

f Next, calculate the flat-band voltage.

$$V_{FB}^{o} = \Phi_M - \Phi_s = 4.05 - 4.877$$

f [5] V_{FB} = $-0.827\ V$. **g** Next, calculate the Fermi potential of the substrate material.

$$\phi_p = \frac{kT}{q} \ln \frac{n_i}{N_A} = 0.025852 \ln \left(\frac{1\times10^{10}}{3\times10^{14}}\right) = -0.267$$

g [4] ϕ_p = $-0.267\ V$. **h** Next, calculate the maximum depletion width at the silicon to silicon-dioxide interface at the onset of strong inversion.

$$X_{d_{max}} = \sqrt{\frac{2\varepsilon_{Si}\, 2|\phi_p|}{q N_A}} = \sqrt{\frac{2\times11.7\times8.85\times10^{-14}\times0.267\times2}{1.6\times10^{-19}\times3\times10^{14}}} = 1.52\times10^{-4}\ cm$$

h [5] $x_{d,max}$ = $1.52\ \mu m$. **i** Next, calculate the depletion charge (per cm^2) at the condition in ~~g~~ h.

$$Q'_{d_{max}} = -q N_a X_d = -1.6\times10^{-19}\times3\times10^{14}\times1.52\times10^{-4} = -7.3\times10^{-9}\ coul/cm^2$$

i [4] $Q'_{d,max}$ = $-7.3\times10^{-9}\ coul/cm^2$. **j** Next, calculate the E-field in the silicon at the silicon-dioxide interface.

$$E_{max} = -\frac{Q'_d}{\varepsilon_{Si}} = \frac{7.3\times10^{-9}}{11.7\times8.85\times10^{-14}} = 7.07\ kV/cm$$

j [4] E_{max} = $21.2\ kV/cm$. **k** Next, calculate the threshold voltage for channel formation in this system.

$$V_T = V_{FB} - 2\phi_p - \frac{Q'_{d\,max}}{C'_{ox}} = -0.827 + 2\times0.267 + \frac{7.3\times10^{-9}}{986\times10^{-9}} = 0.45$$

k [5] V_T = $0.45\ V$.

2 The same system is to be used again, but contacts are made to the channel, such that $V_S = V_D = V_C = 2$ V (V_B=0).
a Calculate the maximum depletion width at the silicon to silicon-dioxide interface at the onset of strong inversion.

$$X_{d\,max} = \sqrt{\frac{2\varepsilon(2|\phi_p| - (V_B - V_c))}{q N_a}} = \sqrt{\frac{2\times 11.7\times 8.85\times10^{-14}\times(2\times0.267+2)}{1.6\times10^{-19}\times 3\times10^{14}}} = 3.3\times10^{-4}\ \text{cm}$$

a [5] $x_{d,max}$ = 3.3 μm. **b** Next, calculate the depletion charge (per cm^2) at the condition in **a**.

$$Q'_{d\,max} = -q N_a X_{d\,max} = -1.6\times10^{-19}\times 3\times10^{14}\times 3.3\times10^{-4} = -1.58\times10^{-8}\ \text{coul/cm}^2$$

b [4] $Q'_{d,max}$ = -1.58×10^{-8} coul/cm^2. **c** Next, calculate the E-field in the silicon at the silicon-dioxide interface.

$$E_{max} = -\frac{Q'_d}{\varepsilon_{Si}} = \frac{1.58\times10^{-8}}{11.7\times 8.85\times10^{-14}} = 15.31\ \text{kV/cm}$$

c [4] E_{max} = 45.9 kV/cm. **d** Next, calculate the threshold voltage for channel formation in this system.

$$V_T = V_{FB} - 2\phi_p - \frac{Q'_{d\,max}}{C'_{ox}} + V_c = -0.827 + 2\times0.267 + \frac{1.58\times10^{-8}}{9.86\times10^{-9}} + 2 = 3.31$$

d [5] V_T = 3.31 V.

3 [Use the model for the MOSFET in the class notes or 8.2.3 of the text.] The same structure given in **1** and **2** is to be used as an n-channel MOSFET. In this case, $V_D > V_S = V_B = 0$
a Calculate the channel charge per cm^2 for $v_{GS} = V_T + 1.5$ V and v_{DS} small.

$$Q'_n = -C'_{ox}(V_{GS} - V_T) = -9.86\times10^{-9}\times 1.5 = -1.48\times10^{-8}\ \text{coul/cm}^2$$

a [5] Q'_n = -1.48×10^{-8} coul/cm^2. **b** Next, calculate the mobility of electrons in the bulk of the p-type silicon.

$$\mu_n = \frac{1360-92}{1+\left(\frac{N}{1.3\times10^{17}}\right)^{0.91}} + 92 = \frac{1360-92}{1+\left(\frac{3\times10^{14}}{1.3\times10^{17}}\right)^{0.91}} + 92$$

$$= 1354$$

b [5] μ_n = 1354 cm^2/V·s.

c Next, make a reasoned estimate of the mobility of electrons in the silicon directly under the silicon-dioxide for $v_{GS} = V_T + 1.5$ V and $V_{DS} = V_{GS}$.

Assume $\mu_{n\,ch} = \frac{1}{2}\mu_n \; (N_A = 3\times10^{14})$

From Fig 3.3 $\mu_n (N_A = 3\times10^{14}) = 1360$ $\qquad \mu_{n\,ch} = 680 \; \mathrm{cm^2/V\cdot s}$

c [3] $\mu_{n,ch} =$ __$680 \; \mathrm{cm^2/V\cdot s}$__. **d** Next, for a channel length, L, of 1E-4 cm and width, W, of 20E-4 cm, calculate the drain current for $v_{GS} = V_T + 1.5$ V and $v_{DS} = V_T$.

from 1K

$V_{GS} > V_T \qquad V_{Dsat} = V_{GS} - V_T = 1.5 \qquad V_{DS} = V_T = 0.45 < V_{Dsat} = 1.5$, linear or ohmic

$$J_D = \frac{W}{L}\mu_n C_{ox}' \left[(V_{GS} - V_T) - V_{DS}/2 \right] \cdot V_{DS} = \frac{20\times10^{-4}}{1\times10^{-4}} \times 680 \times 9.86\times10^{-9} \left[1.5 - 0.225 \right] \cdot 0.$$

$$= 7.7\times10^{-5} \text{ A}$$

d [5] $i_D \doteq$ __77 μA__. **e** Next, for the same conditions, except that $v_{DS} = v_{GS}$, calculate the drain current.

$V_{DS} = V_{GS} \Rightarrow$ Sat.

$$J_D = \frac{W}{2L}\mu_n C_{ox}' (V_{GS} - V_T)^2 = \frac{20\times10^{-4}}{2\times1\times10^{-4}} \times 680 \times 9.86\times10^{-9} \times 1.5^2$$

$$= 1.51\times10^{-4} \text{ A} = 0.15 \text{ mA}$$

e [5] $i_D =$ __0.15 mA__.

4 For the same structure given in **1** and **2** (used as an n-channel MOSFET). **a** Calculate the threshold voltage shift for a source to substrate potential of $V_{SB} = 1.5$ V.

$$\Delta V_T = \frac{\sqrt{2q\varepsilon_{si}N_a}}{C_{ox}'} \left(\sqrt{2|\phi_b| + V_{SB}} - \sqrt{2|\phi_b|} \right) \qquad = 0.7$$

$$= \frac{\sqrt{2\times1.6\times10^{-19}\times11.7\times8.85\times10^{-14}\times3\times10^{14}}}{9.86\times10^{-9}} \left(\sqrt{2\times0.267 + 1.5} - \sqrt{2\times0.267} \right)$$

a [5] $\Delta V_T =$ __0.7 V__. **b** Calculate threshold voltage shift for an extra charge sheet at the silicon to silicon-dioxide interface of (-q)*1E11/cm² when $V_{SB} = 0$.

$$\Delta V_T = \frac{-qN_f}{C_{ox}'} = \frac{+1.6\times10^{-19}\times1\times10^{11}}{9.86\times10^{-9}} = 1.6$$

b [5] $\Delta V_T =$ __1.6 V__.