UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Electrical Engineering and Computer Sciences

EECS 130
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Professor Chenming Hu

Midterm II - Solutions

Name: ________________________________

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Total		100

Problem 1 [20pts]

Answer the following questions concisely:

In a forward-biased P^+N diode,

(a) [5pts] Which type of carrier (electron or hole) dominates the carrier injection across the P-N junction?

Hole.

(b) [5pts] Which type of carrier contributes most of the stored minority carriers?

Hole.

(c) [5pts] Which recombination lifetime (that of the N side or the P side) determines the switching speed of this diode?

N side

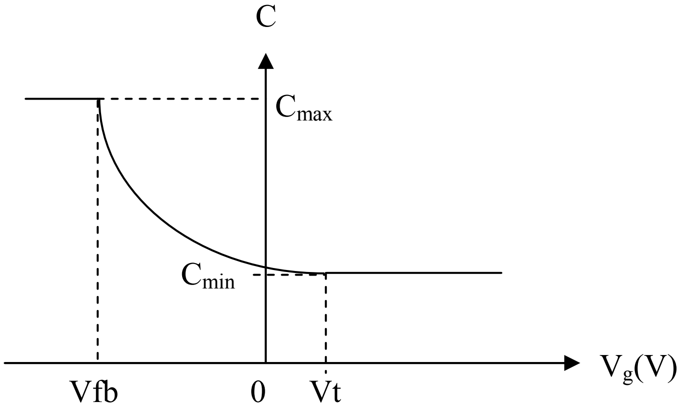
(d) [5pts] Which side has the larger depletion region?

N side

Problem 2 **[20pts]**

Consider a MOS capacitor with N+ polysilicon gate and $N_a = 5\times10^{17}\,cm^{-3}$

(a) [10pts] The C-V characteristic of this MOS capacitor is shown below. Suppose this MOS capacitor is used in a voltage-controlled oscillator, which requires a capacitance tuning range of $\frac{C_{\max}}{C_{\min}} = 1.5$, what's the required oxide thickness (Tox) ? Ignore poly depletion effects and inversion charge thickness effects.



$$C_{dep} = \frac{\varepsilon_s}{W_{dep,\max}} = 2.12\times10^{-7}\,F/cm^2 \qquad \phi_B = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) = 0.46V$$

$$W_{dep,\max} = \sqrt{\frac{2\varepsilon_s 2\phi_B}{qN_a}} = \sqrt{\frac{2\cdot 11.7\cdot 8.854\times10^{-14}\,F/cm\cdot 2\cdot 0.46V}{1.6\times10^{-19}C\cdot 5\times10^{17}cm^{-3}}} = 4.88\times10^{-6}cm = 48.8nm$$

$$C_{\min} = \frac{C_{dep}C_{ox}}{C_{dep}+C_{ox}} \qquad C_{\max} = C_{ox}$$

$$1.5 = \frac{C_{\max}}{C_{\min}} = \frac{C_{dep}+C_{ox}}{C_{dep}} = 1+\frac{C_{ox}}{C_{dep}}$$

$$C_{ox} = 0.5C_{dep} = 1.06\times10^{-7}\,F/cm^2$$

$$T_{ox} = \frac{3.9\cdot 8.854\times10^{-14}\,F/cm}{1.06\times10^{-7}\,F/cm^2} = 3.26\times10^{-6}cm = 32.6nm$$

(b) [5pts] Assume the fixed oxide charge density at the p-type silicon / SiO_2 interface is $N_{it}=10^{12}cm^{-2}$. The charge is positive. What is the flatband voltage, V_{fb}? Assume T_{ox}=10nm. Don't use the T_{ox} calculated in (a).

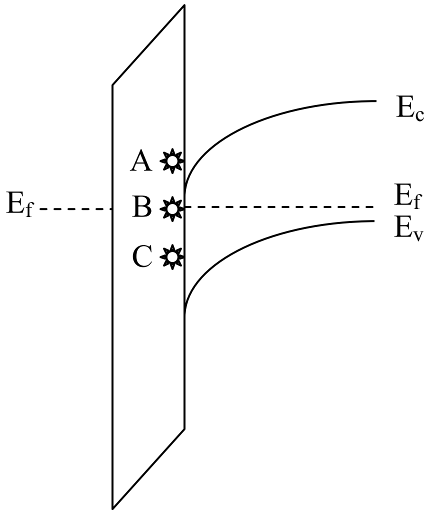
$$C_{ox}=\frac{\varepsilon_{ox}}{T_{ox}}=3.45\times10^{-7}\,{}^{F}\!\big/_{cm^2}$$

$$\frac{qN_{ox}}{C_{ox}}=\frac{1.6\times10^{-19}C\cdot10^{12}\,{}^{1}\!\big/_{cm^2}}{3.45\times10^{-7}\,{}^{F}\!\big/_{cm^2}}=0.46V$$

$$V_{fb}=\Phi_g-\Phi_s-\frac{Q_{ox}}{C_{ox}}=-0.56V-0.026V\cdot\ln\frac{5\times10^{17}}{10^{10}}-\frac{Q_{ox}}{C_{ox}}=-1.02-\frac{qN_{ox}}{C_{ox}}=-1.48$$

(c) [5pts] Assume there are 3 electron traps (electron states), A, B, and C in the SiO_2, as shown below. A is 0.5eV above E_f; B is located at E_f; C is 0.5eV below E_f. What is the probability that

(1) A is filled
(2) B is empty
(3) C is empty



$$f\left(E_A\right)=\frac{1}{1+\exp\left(\frac{E_A-E_f}{kT}\right)}=\frac{1}{1+\exp\left(\frac{500meV}{26meV}\right)}=4.45\times10^{-9}$$

$$f\left(E_B\right)=1-\frac{1}{1+\exp\left(\frac{E_B-E_f}{kT}\right)}=1-\frac{1}{1+\exp(0)}=0.5$$

$$f\left(E_{T,C}\right)=1-\frac{1}{1+\exp\left(\frac{E_{T,C}-E_f}{kT}\right)}=\frac{\exp\left(\frac{E_{T,C}-E_f}{kT}\right)}{1+\exp\left(\frac{E_{T,C}-E_f}{kT}\right)}$$

$$=\frac{4.45\times10^{-9}}{1+4.45\times10^{-9}}=4.45\times10^{-9}$$

Problem 3 [20pts]

An n-channel MOSFET is fabricated on a p-type silicon wafer with $N_a = 10^{17} cm^{-3}$. The gate is N+ polysilicon. $V_t - V_{fb} = 1.2V$, $\mu_{ns} = 300 cm^2 / V - s$, T=300K, m=1.

(a) [5pts] What is the flatband voltage, V_{fb}?

$$V_{fb} = \psi_g - \psi_s = -\frac{E_g}{2q} - \frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right) = -0.56 - 0.026 \cdot \ln\left(\frac{10^{17}}{10^{10}}\right) = -0.98$$

(b) [5pts] If a gate dielectric with a large dielectric constant (high-κ dielectric), $\varepsilon_{ox} / \varepsilon_0 = 25$ is used as the gate dielectric, what is the required oxide thickness (T_{ox}) to achieve $V_t - V_{fb} = 1.2V$?

$$\phi_B = \frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right) = 0.026 \cdot \ln\left(\frac{10^{17}}{10^{10}}\right) = 0.42$$

$$V_t = V_{fb} + 2\phi_B + \frac{\sqrt{2\varepsilon_s q N_a 2\phi_B}}{C_{ox}}$$

$$C_{ox} = \frac{\sqrt{2\varepsilon_s q N_a 2\phi_B}}{V_t - V_{fb} - 2\phi_B}$$

$$= \frac{\sqrt{2 \cdot 11.7 \cdot 8.8542 \times 10^{-14} F/cm \cdot 1.6 \times 10^{-19} C \cdot 10^{17} cm^{-3} \cdot 2 \cdot 0.42}}{1.2 - 2 \cdot 0.42} = 4.64 \times 10^{-7} F/cm^2$$

$$T_{ox} = \frac{\varepsilon_{ox}}{C_{ox}} = \frac{25 \cdot 8.8542 \times 10^{-14} F/cm}{4.64 \times 10^{-7} F/cm^2} = 4.77 \times 10^{-6} cm = 47.7 nm$$

(c) [5pts] If V_{gs}-V_t=1.0V, V_{ds}=1.5V, is the transistor operating in linear region or saturation region?

$$V_{dsat} = \frac{V_{gs} - V_t}{m} = 1.0 < V_{gs} - V_t$$

The transistor is operating in the saturation region

Problem 4. **[20pts]**

Consider an n-channel MOSFET with a P^+ polysilicon gate, a width to length ratio of $W/L = 2$, an oxide thickness of $T_{oxe} = 10nm$, and body doping of $N_a = 5 \times 10^{16} cm^{-3}$.

[5pts] **(a)** Calculate the threshold voltage V_t.

$$\phi_B = \frac{kT}{q} l\, n\left(\frac{N_a}{n_i}\right) = 0.401\ V$$

Since the gate is P⁺ polysilicon gate the flat-band voltage is,

$$V_{fb} = \psi_g - \psi_s = \left(\chi_{Si} + \frac{E_g}{q}\right) - \left(\chi_{Si} + \frac{E_g}{2q} + \phi_B\right) = \frac{E_g}{2q} - \phi_B = 0.159\ V$$

$$\therefore\ V_t = V_{fb} + 2\phi_B + \frac{\sqrt{2\varepsilon_{si} q N_a 2\phi_B}}{C_{ox}} = 0.159 + 0.802 + 0.334 = 1.295\ V$$

[5pts] **(b)** Calculate the body-effect factor m.

$$m = 1 + \frac{3t_{ox}}{W_{dmax}} = 1 + \frac{3t_{ox}}{\sqrt{\frac{2\varepsilon_{si} 2\phi_B}{qN_a}}} = 1.208$$

[5pts] **(c)** Find the drain current I_D at $V_{gs} = 3.5V$ and $V_{ds} = 2V$. Use the values obtained from **(a)** and **(b)**. Assume $\mu_{ns} = 250 cm^2/V \cdot sec$. (If you haven't solved **(a)** and **(b)**, use $V_t = 1V$ and $m = 1.3$.)

*Using results from **(a)** and **(b)**,*

$$V_{dsat} = \frac{V_{gs} - V_t}{m} = \frac{3.5V - 1.295V}{1.208} = 1.825V < V_{ds} = 2V$$

So the transistor is in saturation.

$$\therefore\ I_D = \frac{W}{2mL}\mu_{ns}C_{ox}\left(V_{gs} - V_t\right)^2 = 0.348\, mA$$

Using the given values,

$$V_{dsat} = \frac{V_{gs} - V_t}{m} = \frac{3.5V - 1V}{1.3} = 1.923V < V_{ds} = 2V$$

$$\therefore\ I_D = \frac{W}{2mL}\mu_{ns}C_{ox}\left(V_{gs} - V_t\right)^2 = 0.415\, mA$$

[5pts] **(d)** Determine threshold voltage V_t with a body to source reverse bias of $V_{sb} = 2V$. Assume a constant maximum depletion width of $W_{dmax} = 0.15\mu\text{m}$ with a retrograde doping profile.

$$V_t = V_{t0} + \alpha V_{sb} = V_{t0} + \frac{3t_{ox}}{W_{dmax}} V_{sb}$$

$$= 1.295V + \frac{3 \times (10 \times 10^{-7}\text{cm})}{0.15 \times 10^{-4}\text{cm}} \times 2V$$

$$= 1.295V + 0.2 \times 2V$$

$$= 1.295V + 0.4V$$

$$= 1.695V$$

Problem 5. **[20pts]**

Design an n-channel MOSFET with a polysilicon gate to have a threshold voltage of $V_t = 1V$. Assume an oxide thickness of $T_{oxe} = 10nm$, a channel length of $L = 1\mu m$, and a body-effect factor of $m = 1$.

[5pts] **(a)** What is the standard polysilicon gate doping type for this transistor?

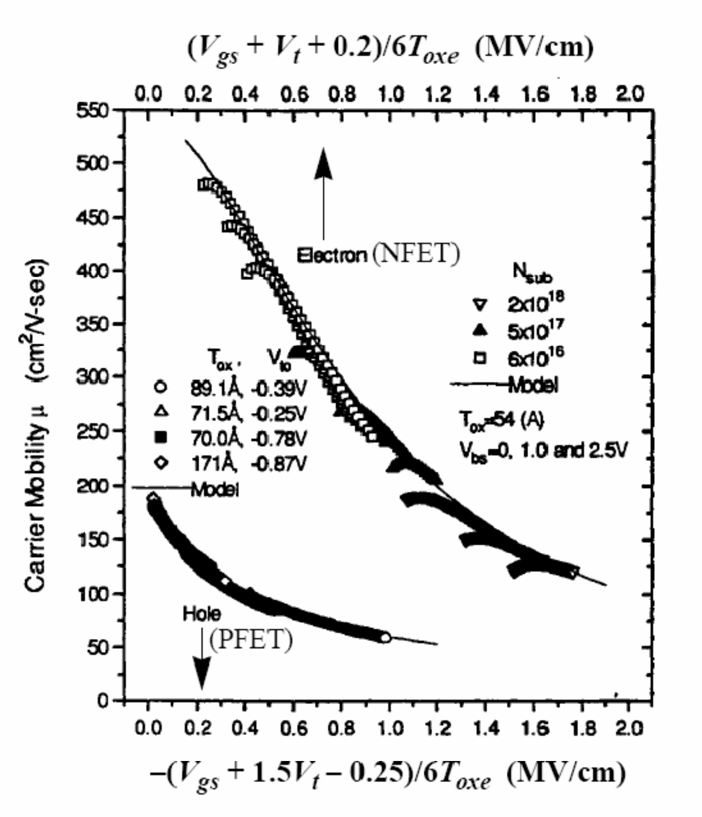
The standard polysilicon gate doping is N^+.

[5pts] **(c)** Determine is the body doping N_a. Assume $\emptyset_B = 0.45V$ but do not determine N_a from $\emptyset_B = (kT/q)\ln{(N_a/n_i)}$.

$$V_t = V_{fb} + 2\phi_B + \frac{\sqrt{2\varepsilon_{si} q N_a 2\phi_B}}{C_{ox}} = -\left(\frac{E_g}{2q} + \phi_B\right) + 2\phi_B + \frac{\sqrt{4\varepsilon_{si} q N_a \phi_B}}{C_{ox}}$$

$$\therefore N_a = \left(V_t + \frac{E_g}{2q} - \phi_B\right)^2 \frac{{C_{ox}}^2}{4\varepsilon_{si} q \phi_B} = 4.924 \times 10^{17}\ cm^{-3}$$

[10pts] **(c)** A drain current of $I_D = 1.35mA$ is required at $V_{gs} = V_{ds} = 3V$. Calculate the required device width W. Use the universal mobility curve given below to find μ_{ns}.



First we find the mobility.

$$\boldsymbol{\mathcal{E}}_{eff} = \frac{V_{gs} + V_t + 0.2V}{6t_{ox}} = \frac{3V + 1V + 0.2V}{6 \times (10 \times 10^{-7} cm)} = 0.7\ MV/cm$$

$$\therefore \mu_{ns} = 325\ cm^2/V \cdot sec$$

Calculating V_{dsat} *show the transistor is in saturation.*

$$V_{dsat} = \frac{V_{gs} - V_t}{m} = \frac{3V - 1V}{1} = 2V < V_{ds} = 3V$$

So the current is written as,

$$I_D = \frac{W}{2mL}\mu_{ns}C_{ox}\left(V_{gs} - V_t\right)^2 = 1.35\ mA$$

$$\therefore W = \frac{2 \cdot m \cdot L \cdot I_D}{\mu_{ns}C_{ox}\left(V_{gs} - V_t\right)^2} = 6.015\ \mu m$$