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

EE 130/230M — Spring 2013
Integrated Circuit Devices — Prof. Liu & Dr. Xu

QUIZ #5
Time allotted: 25 minutes

NAME: SOLUTIONS _____ _____ _____
(print) Last First Signature

1. **Use the values of physical constants provided below. 2. SHOW YOUR WORK, & write legibly!**
2. **Underline or box numerical answers, and SPECIFY UNITS where appropriate.**

Physical Constants

Description	Symbol	Value
Electronic charge	q	1.6×10^{-19} C
Thermal voltage at 300K	kT/q	0.026 V

$(kT/q)\cdot ln(10) = 0.060$ V

Properties of silicon (Si) at 300K

Description	Symbol	Value
Energy band gap	E_G	1.12 eV
Intrinsic carrier concentration	n_i	10^{10} cm^{-3}
Permittivity	ε_{Si}	1.0×10^{-12} F/cm

Problem 1 [15 points]

Consider a n-channel Si MOSFET with $W = L = 1$ μm, effective gate-oxide thickness $T_{oxe} = 3.45$ nm ($C_{oxe} = 10^{-6}$ F/cm^2), gate work function $\Phi_M = 4.03$ eV and bulk Si dopant concentration $N_A = 10^{17}$ cm^{-3} (corresponding to bulk Si work function $\Phi_S = 5.03$ eV and maximum depletion width $W_T = 100$ nm)
Assume $T = 300$K and $V_S = V_B$.

⇒ channel/gate area $= 10^{-8}$ cm^2

$\Rightarrow C_{dep,min} = \frac{10^{-12}}{100\times10^{-6}} = 10^{-7}$ F/cm

(a) If the fixed oxide charge $Q_F = 10^{12}\ q/\text{cm}^2$, what is the flat-band voltage, V_{FB}? [3 pts]

$$V_{FB} = \frac{\Phi_M}{q} - \frac{\Phi_S}{q} - \frac{Q_F}{C_{oxe}} = 4.03 - 5.03 - \frac{(10^{12})(1.6\times10^{-19})}{10^{-6}} = -1.16\text{ V}$$

(b) What is the threshold voltage V_T? [4 pts]
$Q_{dep} = \sqrt{2qN_A\varepsilon_{Si}(2\phi_F)} = 1.6\times10^{-7} C/cm^2$

$$\phi_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) = \frac{kT}{q}\ln\left(\frac{10^{17}}{10^{10}}\right) = 7\times\frac{kT}{q}\ln(10)$$
$$= 7\times0.06\text{V} = 0.42\text{V}$$

$$V_T = V_{FB} + 2(\phi_F) + \frac{Q_{dep}}{C_{oxe}} = -1.16 + 2(0.42) + \frac{1.6\times10^{-7}}{10^{-6}} = -0.16\text{ V}$$

(c) Is this an enhancement-mode or depletion-mode device? Justify your answer. [1 pt]

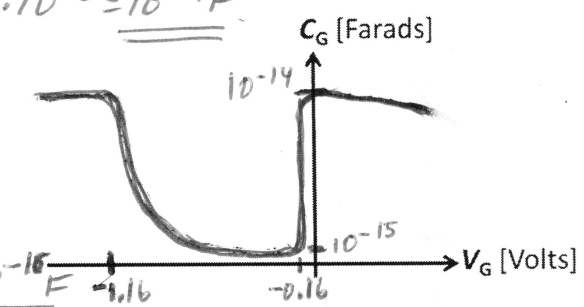
Since $V_T < 0$V and this is an n-channel device, it will be ON for $V_{GS} = 0$V.

(d) Suppose $V_S = V_D = V_B = 0$ V. Sketch the gate capacitance *vs.* gate voltage on the axes provided. [5 pts]
(i) Indicate the maximum value. $C_{max} = A C_{oxe} = 10^{-8}\cdot10^{-6} = 10^{-14}$F
(ii) Estimate the minimum value.
(iii) Indicate V_{FB} and V_T.

$$\frac{C_{min}}{A} = \frac{C_{oxe}C_{dep,min}}{C_{oxe}+C_{dep,min}} = \frac{(10^{-6})(10^{-7})}{10^{-6}+10^{-7}}$$

($A = 10^{-8}$ cm^2)

$$= \frac{10^{-13}}{1.1\times10^{-6}} \simeq 9\times10^{-7}\text{ F/cm}^2 \Rightarrow C_{min} = 9\times10^{-15}\text{ F}$$



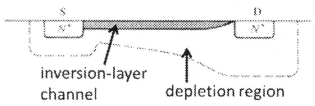
(e) Should acceptor or donor atoms be implanted into the near-surface region of the channel, in order to adjust V_T to be -0.3 V? Provide a brief, qualitative justification for your answer. [2 pts]

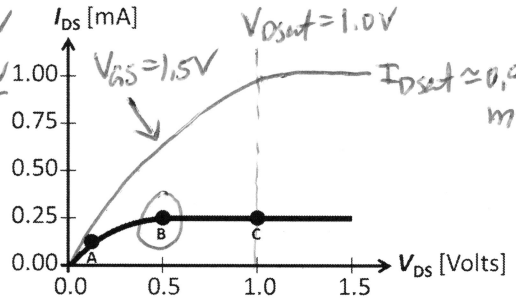
To make the NMOSFET more strongly depletion mode, the surface should be made more n-type, so donor atoms should be added.

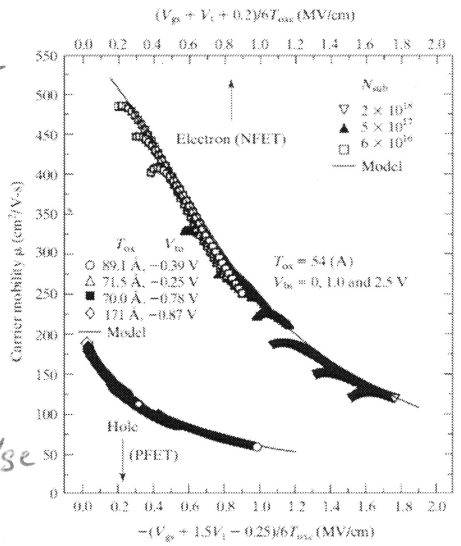
Problem 2 [10 points]

A schematic cross-section of the silicon region within a long n-channel MOSFET with T_{oxe} = 10 nm is shown below with its I_{DS}-V_{DS} characteristic for V_{GS} = 1 V. Assume $V_S = V_B = 0$ V and the bulk charge factor $m \cong 1$.

From the plot, $V_{Dsat} = 0.5V$ $\Rightarrow V_G - V_T = 0.5V \Rightarrow V_T = 0.5V$







(a) Identify the MOSFET operating point on the *I-V* curve above. (Circle the appropriate letter.) [1 pt]

The inversion layer is just pinched off at the drain end, so the MOSFET is operating at the edge of saturation.

(b) Add a curve for V_{GS} = 1.5 V to the plot above. Indicate approximate values for V_{Dsat} and I_{Dsat}; show how you arrived at these values. [4 pts]

- At $V_{GS} = 1.5V$, $V_G - V_T = 1V = V_{Dsat}$ is 2X larger than at $V_{GS} = 1.0V$, so $(V_{GS} - V_T)^2$ is 4X larger.
- At $V_{GS} = 1.0V$, $(V_{GS}+V_T+0.2)/6T_{oxe} = \frac{1.0+0.5+0.2}{6\times10\times10^{-7}} \cong 0.28$ MV/cm, $\mu_{eff} \cong 475$ cm²/V·s

  At $V_{GS} = 1.5V$, $(V_{GS}+V_T+0.2)/6T_{oxe} = \frac{1.5+0.5+0.2}{6\times10\times10^{-7}} \cong 0.37$ MV/cm, $\mu_{eff} \cong 450$ cm²/V·s

  → μ_{eff} decreases by ~5%

Therefore I_{Dsat} increases by 4X · 95% $\Rightarrow I_{Dsat} \cong 0.95$ mA

(c) Qualitatively, why does the saturation current (I_{Dsat}) of a long-channel MOSFET increase ~quadratically with gate overdrive (V_{GS}–V_T)? [3 pts]

MOSFET current is proportional to the inversion-layer charge density (Q_{inv}) and the carrier drift velocity (v):

- Q_{inv} increases linearly with $V_{GS}-V_T$
- The maximum drift velocity increases with $V_{GS}-V_T$ since this is the largest voltage that is applied across the inversion layer.

(d) What is the body effect? Provide a qualitative explanation for it. [2 pts]

The body effect refers to the increase in $|V_T|$ with reverse biasing of the source-body p-n junction, due to an increase in Q_{dep} and hence reduced $Q_{inv} \propto (V_G - V_T)$.