April 18, 2001 - Quiz #2

Name: ________________________________

Recitation: __________________________

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General guidelines (please read carefully before starting):

- Make sure to write your name on the space designated above.
- Open book: you can use any material you wish.
- All answers should be given in the space provided. Please do not turn in any extra material. If you need more space, use the back page.
- You have 120 minutes to complete your quiz.
- Make reasonable approximations and state them, i.e. quasi-neutrality, depletion approximation, etc.
- Partial credit will be given for setting up problems without calculations. NO credit will be given for answers without reasons.
- Use the symbols utilized in class for the various physical parameters, i.e. $\mu_n, I_D, E$, etc.
- Every numerical answer must have the proper units next to it. Points will be subtracted for answers without units or with wrong units.
- Use $\phi = 0$ at $n_o = p_o = n_i$ as potential reference.
- Use the following fundamental constants and physical parameters for silicon and silicon dioxide at room temperature:

\[
\begin{align*}
n_i &= 1 \times 10^{10} \text{ cm}^{-3} \\
kT/q &= 0.025 \text{ V} \\
q &= 1.60 \times 10^{-19} \text{ C} \\
\epsilon_s &= 1.05 \times 10^{-12} \text{ F/cm} \\
\epsilon_{ox} &= 3.45 \times 10^{-13} \text{ F/cm}
\end{align*}
\]
1. (25 points) You are given a CMOS inverter with the following parameters:

\[ V_{Tn} = 0.5 \text{ V} \quad t_{ox} = 10 \text{ nm} \quad \mu_n = 400 \text{ cm}^2/\text{V} \cdot \text{s} \]
\[ V_{Tp} = -1 \text{ V} \quad \lambda_n = \lambda_p = 0.1 \text{ V}^{-1} \quad \mu_p = 200 \text{ cm}^2/\text{V} \cdot \text{s} \]
\[ V_{DD} = 5 \text{ V} \quad L_n = L_p = 1 \mu\text{m} \]

(1a) (5 points) Calculate the ratio \( W_p/W_n \) so that \( V_M = 2.5 \text{ V} \).
(1b) (5 points) We want this inverter to have an average propagation delay \( t_p = 1 \) ns when driving a \( C_L = 1 \) pF capacitive load. Calculate \( W_n \) and \( W_p \).
(1c) (10 points) Estimate $NM_L$ and $NM_H$ for this inverter.
(1d) (5 points) Sketch and appropriately label the voltage transfer characteristics of this inverter.
2. *(20 points)* You are given the following I-V characteristics for a n-MOSFET with $t_{ox} = 10 \text{ nm}$, $W = 10 \mu \text{m}$, and $L = 1 \mu \text{m}$. The gate material is n$^+$-doped polysilicon. The body is tied up to the source.

\begin{align*}
\text{In (A), } g_m &= 1.4 \times 10^{-4} \text{ A/V. In (B), } g_o = 5.7 \times 10^{-5} \text{ A/V.}
\end{align*}

(2a) *(5 points)* From (A), estimate the threshold voltage, $V_T$. 
(2b) (5 points) From (A), estimate the electron mobility, $\mu_n$. 
(2d) (5 points) Estimate the saturation voltage, $V_{DSat}$, and the saturation current, $I_{Sat}$, corresponding to the characteristics in (B).

(2e) (5 points) From (B), estimate the length of the channel pinch-off region, $\Delta L$, at $V_{DS} = 4 \text{ V}$. 
3. \( (20 \text{ points}) \) An n-channel MOSFET is wired up in the form indicated below. This is an enhancement-mode device \((V_T > 0)\). Neglect channel length modulation.

\[ \text{I} \sha \begin{array}{c} \text{+} \\ \text{V} \\ \text{-} \end{array} \]

(3a) \( (10 \text{ points}) \) In terms of usual MOSFET parameters, derive suitable equations for the I-V characteristics of the resulting two-terminal device. Sketch the I-V characteristics in a linear scale.
(3b) (10 points) Sketch a complete high-frequency small-signal equivalent circuit model for this two-terminal device for situations in which $V > V_T$. Express all small-signal elements in terms of those of the MOSFET, i.e.: as a function of $g_m$, $g_o$, $C_{gs}$, $C_{gd}$, $C_{sb}$, etc.
4. (15 points) An NMOS inverter with a resistor pull up was miswired and ended up as sketched below.

![Diagram of an NMOS inverter with a resistor pull up](image)

The parameters of the transistor are: $\mu_n C_{ox} = 50 \mu A/V^2$, $W/L = 5$, and $V_T = 1 V$. Neglect channel length modulation in this problem.

(4a) (5 points) For $V_{IN} = 0$, in what regime is the transistor biased? How much is $V_{OUT}$? (numerical answer expected).
(4b) (10 points) For $V_{IN} = 5 \, V$, in what regime is the transistor biased? How much is $V_{OUT}$? (you can leave the result in the form of an equation where $V_{OUT}$ is the only unknown).
5. (20 points) In a certain pn junction diode at room temperature at a particular forward bias voltage, the current supported by hole injection into the n-side of the diode is 100 $\mu$A.

The quasi-neutral width of the n-side of the diode is $w_n - x_n = 1 \mu m$. The hole diffusion coefficient is $10 \, cm^2/s$. The pn junction area is $10 \, \mu m^2$.

Make and state suitable approximations.

(5a) (5 points) Estimate the hole concentration at the space-charge region edge of the n quasi-neutral region. (numerical answer expected).

(5b) (5 points) Estimate the velocity at which holes are injected at the edge of the n quasi-neutral region (numerical answer expected).
(5c) (5 points) Estimate the hole flux arriving at the surface of the n quasi-neutral region. (numerical answer expected).

(5d) (5 points) Estimate the diffusion capacitance associated with hole storage in the n quasi-neutral region. (numerical answer expected).