ECE 3040 Microelectronic Circuits

Exam 3

April 18, 2008

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Print your name clearly and largely: Solutions

Instructions:
DO NOT TAKE APART ANY PAGES OF THIS EXAM AND SHOW ALL WORK ON THE PROVIDED PAGES. Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back), your two note sheets from the previous exams as well as a calculator. There are 100 total points in this exam. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered a wrong answer. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

Sign your name on **ONE** of the two following cases:

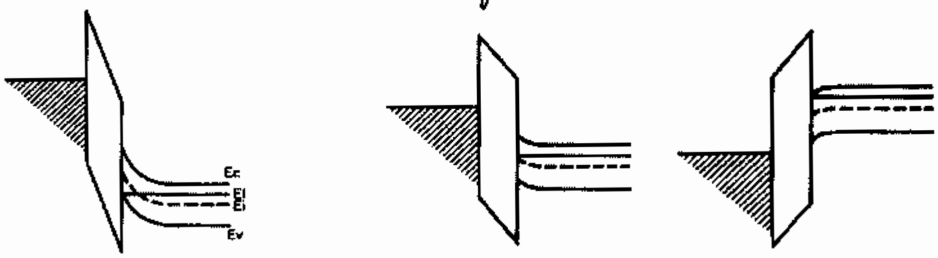
I DID NOT observe any ethical violations during this exam: ______________________

I observed an ethical violation during this exam: ______________________

First 30% **Multiple Choice and True/False (Select the most correct answer)**

1.) (6-points total) Identify the bias mode of the following MOS capacitors.

(A) Inversion (B) Depletion (C) Accumulation



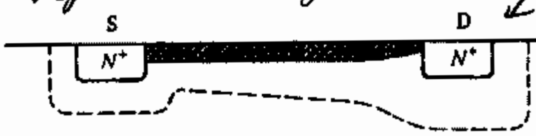
2.) (4-points) For a MOS Capacitor...

(all 4)

a) ...it can be used to form a charge storage element in a memory circuit.
b) ...it can be used as a frequency tuning element in an amplifier.
c) ...it's capacitance will never be greater than when biased into accumulation.
d) ...it's capacitance will never be smaller than when biased in inversion.
e) None of the above.

3.) (4-points) True / False The transistor to the right is biased in linear/triode mode and has a zero volt V_{DS}.

Depletion is higher at Drain end & indicates $V_D > V_{Body}$



4.) (4-points) In the MOSFET transistor to the right, ~~what is the voltage across the pinched-off region?~~

a.) $V_{GS}-V_T > V_{DS}$
b.) V_{DB} is reverse biased
c.) $V_{DS}>V_{Dsat}$
d.) $V_{GS}-V_T < V_{DS}$
e.) Not enough information given to solve

$\frac{V_{out}}{i_{in}}$ =

5.) (3-points) True / False: A well designed transresistance amplifier should have a very low input resistance. Get current into the amplifier

6.) (3-points) True / False: A well designed transresistance amplifier should have a very low output resistance. Get all voltage delivered to the load

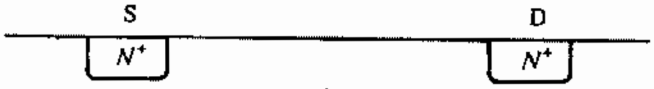
7.) (3-points) True/False: The body of a PMOS Enhancement mode transistor should be tied to the most positive potential in order to maintain the Body-Drain reverse biased. V_{DB} should be reverse biased

8.) (3-points) The region beneath the channel of a PMOS transistor biased into saturation is extremely ~~high resistivity~~ due to this region being depleted of carriers.

True

9.) (20-points) The MOSFET below is doped (initially) at N_A=1e16 cm^{-3} . It is desired to use "ion implantation" to increase the channel doping to adjust the turn on voltage to be 1.5 volts. What new doping concentration is needed?

K_{Si}=11.8
K_{oxide}=3.9
X_{oxide} (oxide thickness)=30 angstroms
(an angstrom = 1×10^{-10} m)
n_i (Silicon intrinsic concentration)=1×10^{10} cm^{-3}



p-type

$$\phi_F = \begin{cases} \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) & \text{for a p-type semiconductor} \\ -\frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right) & \text{for a n-type semiconductor} \end{cases}$$

$\Rightarrow \phi_{F_{initially}} = 0.0259 \ln\left(\frac{10^{16}}{10^{10}}\right) = 0.3578\,V$ — Note! Not Needed

$$V_T = 2\phi_F + \frac{\varepsilon_S}{C_{ox}}\sqrt{\frac{2qN_A}{\varepsilon_S}(2\phi_F)} \quad \text{(for n-channel devices)}$$

$V_{T_{initially}} = 0.758$

$$V_T = 2\phi_F - \frac{\varepsilon_S}{C_{ox}}\sqrt{\frac{2qN_D}{\varepsilon_S}(-2\phi_F)} \quad \text{(for p-channel devices)}$$

where,

$C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}}$ is the oxide capacitance per unit area

$$C_{ox} = \frac{3.9 \times 8.854\times10^{-14}\ F/cm}{30\times10^{-8}\ cm} = 1.151\times10^{-6}\ F/cm^2$$

$$\epsilon_S = 11.8 \times 8.854\times10^{-14} = 1.0447\times10^{-12}\ F/cm^2$$

$$1.5V = V_T = 2\frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) + \left(\frac{2\epsilon_S}{C_{ox}}\sqrt{\frac{q}{\epsilon_S}}\right)\sqrt{N_A}\sqrt{\frac{kT}{q}}\sqrt{\ln\left(\frac{N_A}{n_i}\right)}$$

$$= 0.0518\ln\left(\frac{N_A}{1e10}\right) + (1.143\times10^{-10})\left[\sqrt{N_A \ln\left(\frac{N_A}{1\times10^{10}}\right)}\right]$$

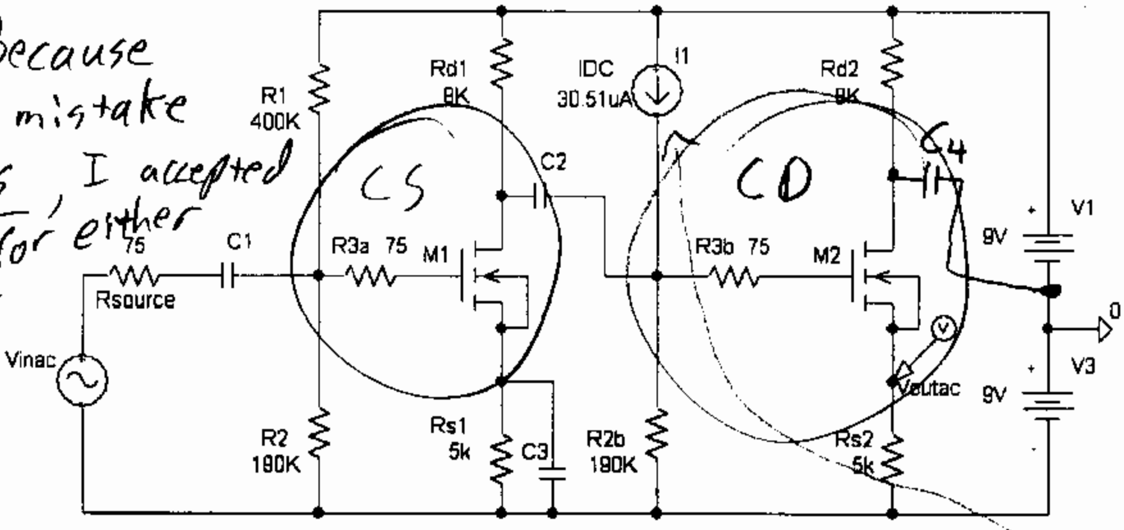
Solution by iteration (or Calculator)

N_A	V_T
1e16	0.758
1e17	0.98
1e18	1.445 ← close enough but ...
1.5e18	~~1.583~~
1.2e18 cm^{-3}	**1.504**

Pulling all the concepts together for a useful purpose:

10 ~~85~~ ***(50-points)*** Given the following circuit, (a) Identify the configuration of ***BOTH*** of the two stages (common ____). (b) What is the AC voltage gain, V_{outac}/V_{inac}? You may assume all capacitors have infinite capacitance. Additionally consider the circuit to be operated at low frequencies where you can neglect all small signal capacitances. Grading will be based as such: part a=5 points, part b=18 points for DC solution (gate, source and drain voltages along with drain currents), 9 points for the conversion to the small signal model and 18 points for small signal analysis. Hint: Noting similarities in the DC solution will greatly speed up your solution. **SHOW ALL WORK TO GET CREDIT!!!!!**

Note: Because of my mistake in class, I accepted either answers for $\lambda = 0.1$ or $\lambda = 0$.



Use the following parameters (note that V_T and λ vary with transistor type):

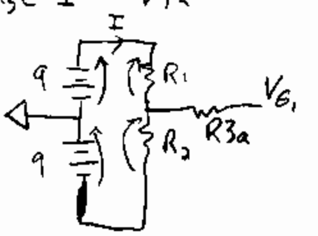
For NMOS Depletion Transistors:
K_n'=200 uA/V² **V_T= -4.0V** **λ=0.0 V⁻¹** Length (L)= 0.18 um Width (W)=10 um

For NMOS Enhancement Transistors:
K_n'=100 uA/V² **V_T= +0.5V** **λ=0.1 V⁻¹** Length (L)=0.18 um Width (W)=5 um

For PMOS Depletion Transistors:
K_p'=400 uA/V² **V_T= +3.0V** **λ=0.0 V⁻¹** Length (L)=0.36 um Width (W)=10 um

For PMOS Enhancement Transistors:
K_p'=50 uA/V² **V_T= -0.75V** **λ=0.1 V⁻¹** Length (L)=0.36 um Width (W)=5 um

DC: Stage 1 V_{Th}



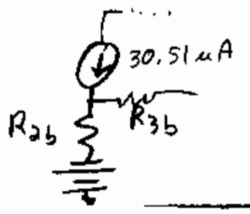
$R_{th} = R_{3a} + R_1 \| R_2 = 128.8\,K$

$I = \frac{9-(-9)}{400K + 190K} = 30.51\,\mu A$ ← Note same as IDC

$V_{G1} = -9 + I R_2 = -9 + (30.51\,\mu A)\,190K$

$V_{G1} = -3.2\ V$

Stage 2 V_{Th}

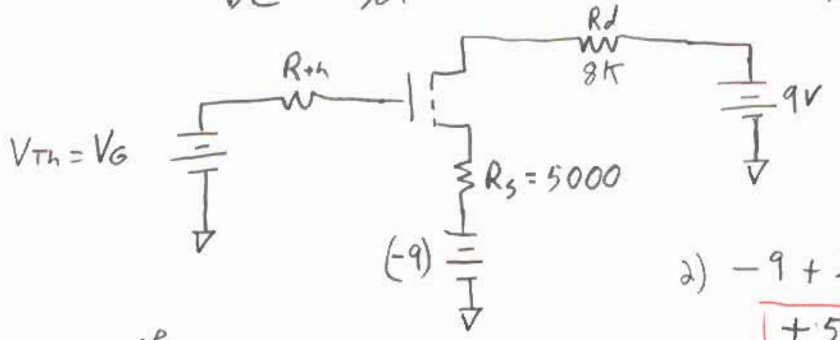


$V_{G2} = 30.51\,\mu A\,(190K) - 9V$
$= -3.2\,V$

same

Extra work can be done here, but clearly indicate with problem you are solving.

DC solution for both stages:



1) $-9 + I_D R_S + V_{DS} + I_D R_d - 9 = 0$

$$18 = I_D(R_S + R_d) + V_{DS}$$

2) $-9 + I_D R_S + V_{GS} - V_{Th} = 0$

$$+5.8 = I_D\,5K + V_{GS}$$

$\lambda = 0.1$ case

$$I_{DS} = \tfrac{1}{2}\left(K_n' \tfrac{W}{L}\right)(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

$$I_{DS} = \tfrac{1}{2}(0.0027)(+5.8 - I_D 5000 - 0.5)^2(1 + 0.1(18 - I_D(13{,}000)))$$

$$\tfrac{1}{2}(0.0027)(33.64 - 117{,}000 I_D + 25\times10^{6} I_D^2)(1 + 1.8 - I_D 1300)$$

$$= \tfrac{1}{2}(0.0934 - 325 I_D + 69{,}444 I_D^2)(2.8 - 1300 I_D)$$

$$= \tfrac{1}{2}[0.2616 - 910 I_D + 194{,}444 I_D^2 - 121.47 I_D + 422{,}500 I_D^2 \ldots$$
$$\ldots - 90{,}277{,}777 I_D^3]$$

$$0 = \tfrac{1}{2}[0.2616 - 1031.47 I_D + 616{,}944 I_D^2 - 90{,}277{,}777 I_D^3] - I_{DS}$$

$$0 = 0.1308 - 516.74 I_D + 308{,}472 I_D^2 - 45{,}138{,}888.5 I_D^3$$

$I_D = 930\,\mu A$

$V_{DS} = 18 - I_D(R_S + R_d) = 5.91\ V$

$V_{GS} = 5.8 - I_D\,5K = 1.15\ V$

$V_{GS} - V_T = 0.65V < 5.91V = V_{DS}$

Saturation ✓

$\lambda = 0.0$ case: $(1 + \lambda V_{DS}) \to 1$ in above

$I_D = 9e{-}4$ A or $900\,\mu A$

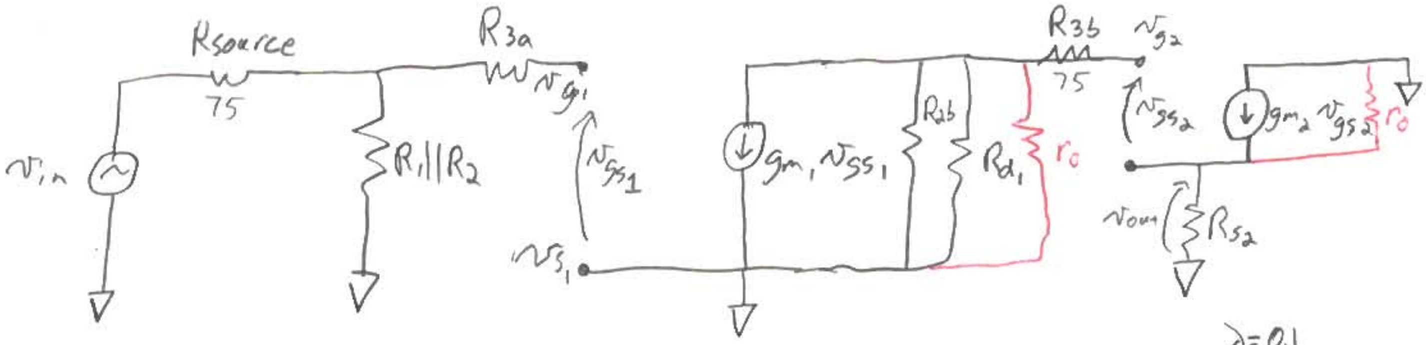
$V_{DS} = 6.31\ V$

$V_{GS} = 1.3\ V$

conversion

Red indicates circuit for $\lambda = 0.1$

Extra work can be done here, but clearly indicate with problem you are solving.



$\lambda = 0.1$: $g_m = 2.87e{-3}\,S$

$\lambda = 0$ case: $g_{m1} = g_{m2} = \dfrac{I_{DS}}{\left(\dfrac{V_{GS} - V_{TN}}{2}\right)} = \dfrac{900\,\mu A}{\left(\dfrac{1.3 - 0.5}{2}\right)} = 2.23e{-3}\ S$

$\lambda = 0$ case: $r_{o1} = r_{o2} = \dfrac{\frac{1}{\lambda} + V_{DS}}{I_{DS}} = \infty$

$\lambda = 0.1$ case: $r_{o1} = r_{o2} = \dfrac{10 + 5.91}{930\,\mu A} = 17.1K$

AC $\lambda = 0$ case:

① $\dfrac{v_{gs1}}{v_{in}} = \left(\dfrac{R_1 || R_2}{R_1 || R_2 + R_{source}}\right) = \dfrac{128.8K}{128.8K + 75} \sim 1\ V/V$

② $\dfrac{v_{g2}}{v_{gs1}} = -(g_{m1}\, R_{d1} || R_{2b}) = -17.11\ V/V$

$v_{g2} = v_{gs2} + v_{out}$ where $v_{out} = g_{m2} v_{gs2} R_{s2}$

④ $\dfrac{v_{out}}{v_{gs2}} = g_{m2} R_{s2} = 11.15\ V/V$

$v_{g2} = v_{gs2} + g_m v_{gs2} R_{s2}$

③ $\dfrac{v_{gs2}}{v_{g2}} = \left(\dfrac{1}{1 + g_m R_{s2}}\right) = \dfrac{1}{1 + (2.23e{-3})\,5000} = \dfrac{1}{12.15} = 0.823\ V/V$

$Av = \left(\dfrac{v_{out}}{v_{in}}\right) = \left(\dfrac{v_{gs1}}{v_{in}}\right)\left(\dfrac{v_{g2}}{v_{gs1}}\right)\left(\dfrac{v_{gs2}}{v_{g2}}\right)\left(\dfrac{v_{out}}{v_{gs2}}\right)$

$= (1)(-17.11)\left(\dfrac{1}{12.15}\right)(11.15)$

$Av = -15.7\ V/V$

Extra work can be done here, but clearly indicate with problem you are solving.

AC case with $\lambda = 0.1$ use $g_{m(\lambda=0.1)} = 2.87e\text{-}3\,S$

In (2) Replace: $R_{d1} \| R_{2b}$ with $R_{d1} \| R_{2b} \| r_o$

$$\frac{v_{g2}}{v_{gs1}} = -15.16\ V/V$$

In (3) + (4) Replase R_{s2} with $R_{s2} \| r_o$

$$\frac{v_{gs2}}{v_{g2}} = \frac{1}{12.07}$$

$$\frac{v_{out}}{v_{gs2}} = 11.07$$

$$A_v = (1)(-15.16)\left(\frac{1}{12.07}\right)(11.07)$$

$$\boxed{A_{v\,\lambda=0.1} = -13.9\ V/V}$$