# ECE 3040 Microelectronic Circuits

*Exam 3*

60 exams
#s 6, 22, 23 not used

*April 15, 2004, Tax payment day!*

*One day soon, you will join the work force and be forced at the point of a gun to give the government 50% of what you earn (local, state, federal, social security and sales taxes)! That goal is what you are studying so hard for! Negotiate a good salary-you will need it!*

*Dr. W. Alan Doolittle*

Solution

Print your name clearly and largely:

**Instructions:**

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 note sheet 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!

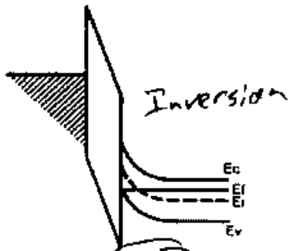
Sign your name on **ONE** of the two following cases:

I DID NOT observe any ethical violations during this exam:

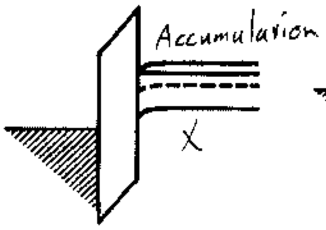
I observed an ethical violation during this exam:

## *First 25%* Multiple Choice and True/False (Select the most correct answer) (5)

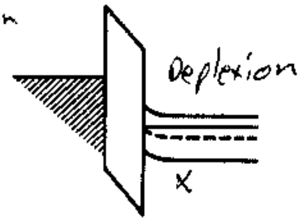
1.) (5-points) A MOS capacitor is used on an enhancement mode MOSFET. When the MOSFET is conducting current, which of the following energy band diagrams would be correct for the MOS capacitor.



[✓ (A)]

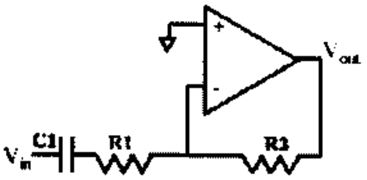


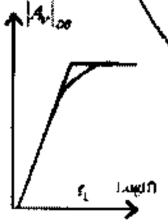
(B)



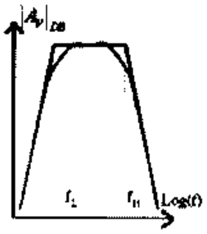
(C)

2.) (5-points) The amplifier below has which of the following filter shapes (circle the correct filter shape)?

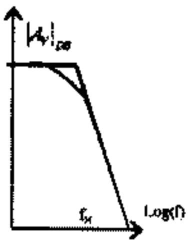




[✓ a)]

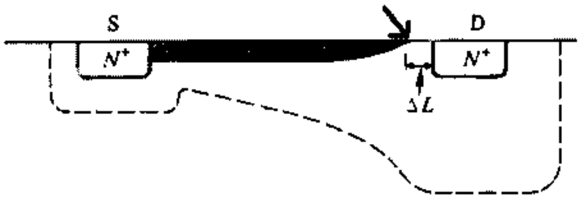


b)



c)

3.) (5-points) In the MOSFET transistor to the right, what is the voltage at the point in the channel indicated by the arrow?



a.) $V_{DS}-V_T$

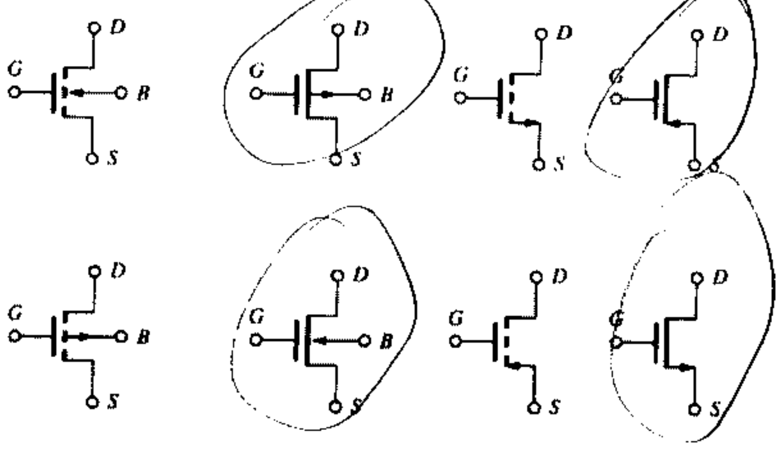
b.) $V_{DS}$

[✓ c.) $V_{D\text{-}sat}$]

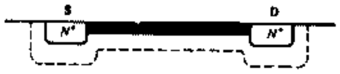
[✓ d.) $V_{GS}-V_T$]

e.) Not enough information given to solve

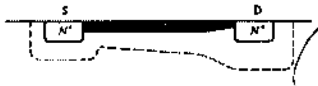
4.) (4-points) Circle ALL the depletion mode transistors below…



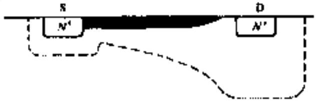
5.) (3-points) Which of the following MOSFET cross sectional views is NOT of a transistor biased in linear mode?



(A)



(B)

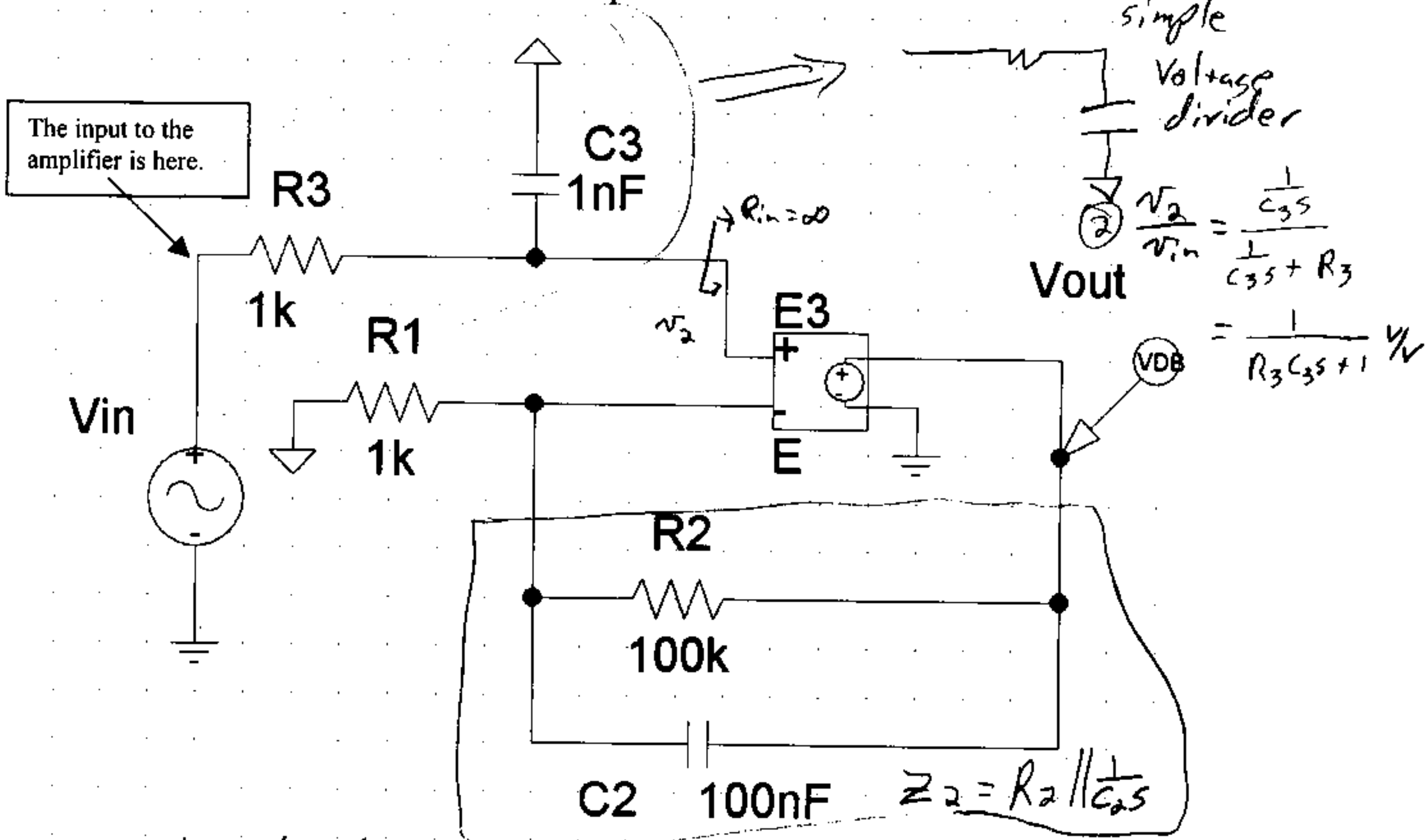


(C)

6.) (3-points) True / [✓ False] Gauss's law as applied to the oxide-semiconductor interface states that the electric field in the semiconductor is equal to the electric field in the oxide.

***Second 25%*** Problems (3rd 25%)

7.) (15-points) Sketch and label all break frequencies, the voltage gain in flat regions in a Bode plot (gain in dB vs Log(frequency)). You may assume that the Op-Amps are ideal. To receive full credit the asymptotes and an estimate of the actual gain curve should BOTH be sketched on the same plot.



② $\frac{v_2}{v_{in}} = \frac{\frac{1}{C_3 s}}{\frac{1}{C_3 s}+R_3} = \frac{1}{R_3C_3s+1}$ V/V

$Z_2 = R_2 \| \frac{1}{C_2 s}$

Non inverting Stage:

① $\frac{v_{out}}{v_2} = 1 + \frac{R_2}{R_1}$ Replace $\Longrightarrow$ $\frac{v_{out}}{v_2} = 1 + \frac{R_2 \| \frac{1}{C_2 s}}{R_1}$

$$= 1 + \frac{\frac{R_2 \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}}{R_1} = \frac{\frac{R_2}{R_2C_2s+1} + R_1}{R_1}\left[\frac{(R_2C_2s+1)}{(R_2C_2s+1)}\right]$$

$$= \frac{R_2 + R_1(R_2C_2s+1)}{(R_2C_2s+1)R_1}$$

$$= \frac{R_2 + R_1 + R_1R_2C_2s}{R_1(1+R_2C_2s)}$$

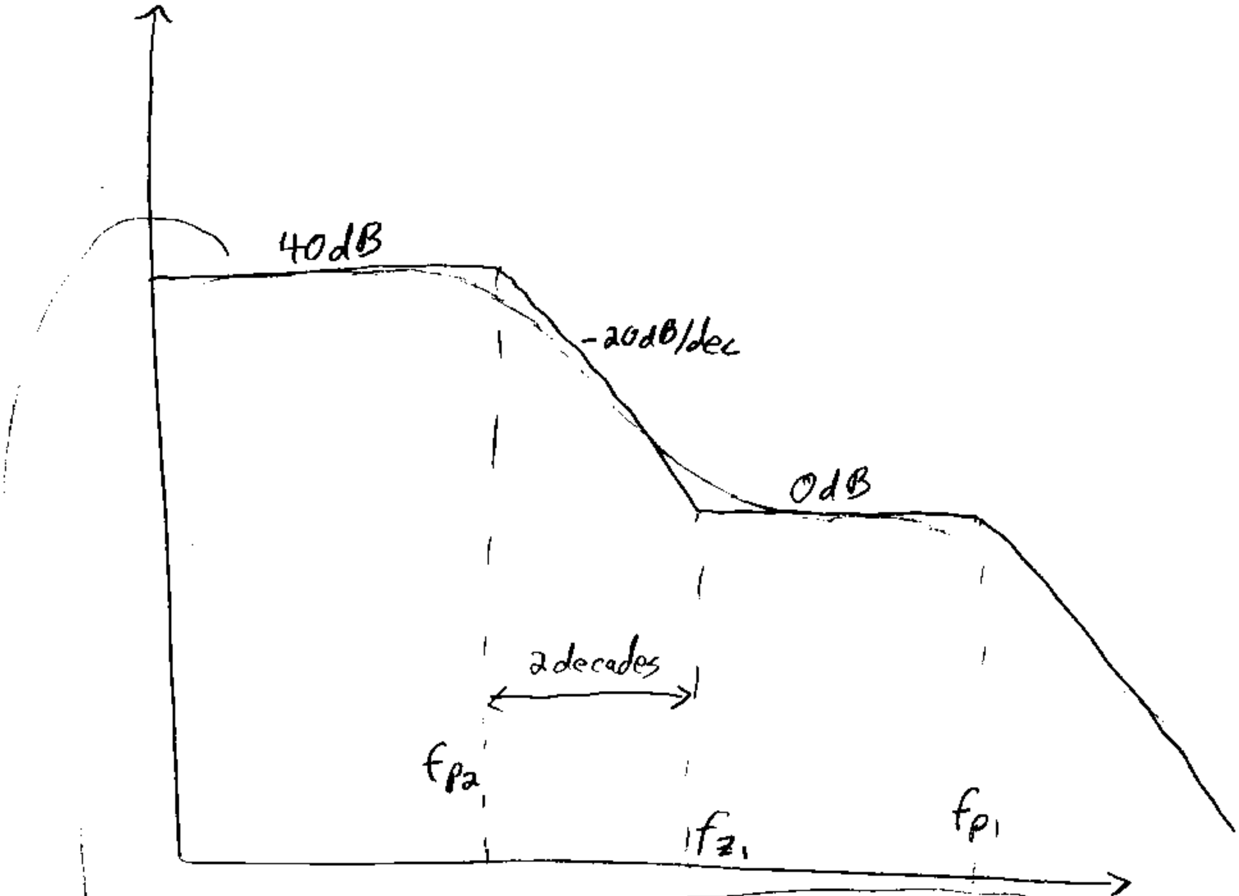
$$= \frac{(R_2+R_1)\left[1 + \frac{R_1R_2}{R_1+R_2}C_2s\right]}{R_1(1+R_2C_2s)}$$

$$\boxed{\frac{v_{out}}{v_2} = \left[1 + \frac{R_2}{R_1}\right]\frac{1+(R_1\|R_2)C_2s}{1+R_2C_2s} \text{ V/V}}$$

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

$$\frac{v_{out}}{v_{in}} = \overset{①}{\frac{v_{out}}{v_2}}\ \overset{②}{\frac{v_2}{v_1}} = \frac{1}{R_3C_3s+1}\left(\frac{1+R_1||R_2C_2s}{1+R_2C_2s}\right)\left(1+\frac{R_2}{R_1}\right)$$

$$\boxed{\begin{array}{ll} f_{p_1} = \dfrac{1}{2\pi R_3C_3} = 159\text{ kHz} & f_{z_1} = \dfrac{1}{2\pi(R_1||R_2)C_2} = 1.6\text{ kHz} \\ f_{p_2} = \dfrac{1}{2\pi R_2C_2} = 15.9\text{ Hz} & \end{array}}$$



$$\boxed{20\log\left(1+\frac{100k}{1k}\right) = 40.08\,dB}$$

$A_v = 101$ V/V

8.) (10-points) The same circuit for problem 7 is used with an Op-Amp designed by a Clemson engineer. This Op-Amp only has an open loop gain of $A_{v\text{-openloop}}$=1000 V/V, $R_{in}$=10K ohms, and $R_{out}$=500 ohms. ***AT DC*** (i.e. open circuit any capacitors) determine the voltage gain, input resistance and output resistance of the circuit. DO NOT USE THE IDEAL OP-AMP ASSUMPTION. Hint: you may find it helpful to determine the feedback factor, β as part of your solution.

$$\beta = \frac{R_1}{R_1 + R_2} = \frac{1k}{100k + 1k} = \frac{1}{101}$$

$$A_{v\,closed\text{-}loop} = \frac{A_{v\,open\,loop}}{1 + \beta A_{v\text{-}openloop}} = \frac{1000}{1 + \frac{1}{101}(1000)}$$

$$\boxed{A_{v\,closed\,loop} = 91.73\ V/V}$$

$$R_{in\text{-}closed\,loop} = (1 + \beta A_{v\,openloop})\, R_{in\text{-}open} + R_3 = \left[1 + \frac{1}{101}(1000)\right] 10K + 1K$$

$$\boxed{R_{in\text{-}closed} = 110\ K\ \Omega}$$

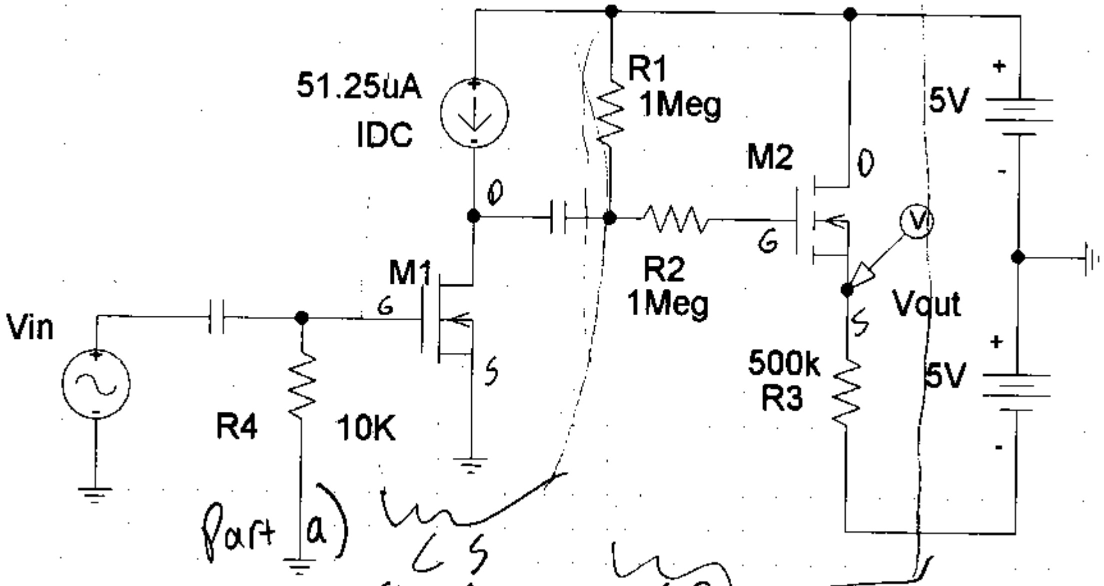
$$R_{out\,closed} = \frac{R_{out\,open}}{1 + \beta A_{v\,openloop}} \,\|\, (R_1 + R_2)$$

$$= \frac{500}{\left[1 + \frac{1}{101}(1000)\right]}$$

$$\boxed{R_{out\text{-}closed} = 45.9\ \Omega}$$

Pulling all the concepts together for a useful purpose: (4th 25%)

9.) ***(50-points)*** Given the following circuit, (a) Identify the configuration of the two stages (common ____). (b) What is the AC voltage gain, $V_{out}/V_{in}$? You may assume all capacitors have infinite capacitance and are thus, AC shorts. 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 current), 9 points for the conversion to the small signal model and 18 points for small signal analysis.



Part a) CS
Stage 1
CD
Stage 2

Use the following parameters (note that $V_T$ and $\lambda$ vary with transistor type):

For NMOS Depletion Transistors:

M1 $K_n'$=25 uA/V$^2$ **$V_T$= -2.0V** **$\lambda$=0.01 V$^{-1}$** Length (L)=10 um Width (W)=10 um

For NMOS Enhancement Transistors:

M2 $K_n'$=25 uA/V$^2$ **$V_T$= +0.75V** **$\lambda$=0.0 V$^{-1}$** Length (L)=10 um Width (W)=10 um

For PMOS Depletion Transistors:

$K_n'$=25 uA/V$^2$ **$V_T$= +3.0V** **$\lambda$=0.01 V$^{-1}$** Length (L)=10 um Width (W)=10 um

For PMOS Enhancement Transistors:

$K_n'$=25 uA/V$^2$ **$V_T$= -1.75V** **$\lambda$=0.0 V$^{-1}$** Length (L)=10 um Width (W)=10 um

DC M1 Assume Saturation:

$$51.25uA = \frac{25e\text{-}6}{2}\left(\frac{10}{10}\right)\left(V_{GS_1}-(-2.0)\right)^2\left(1+0.01V_{DS_1}\right)$$

but $V_{GS_1}=0$

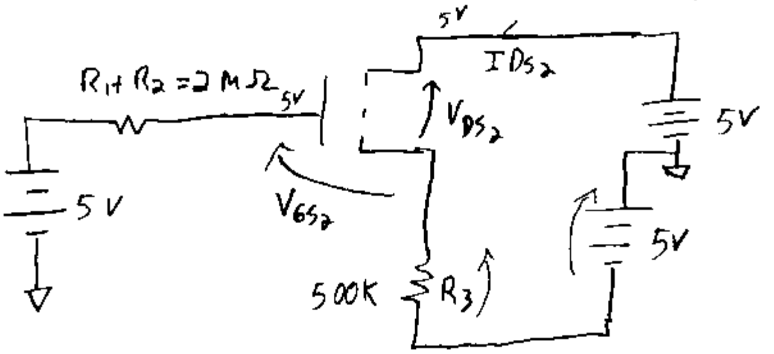
$$51.25e\text{-}6 = 50e\text{-}6\left(1+0.01V_{DS_1}\right)$$

$$V_{DS_1} = 2.5V$$

check assumption: $V_{DS_1} > V_{GS_1} - V_T \Rightarrow 2.5V > 0 - -2$

$2.5V > 2V$ ✓

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



Assume Saturation:

$$\frac{10}{10}$$

$$I_{DS_2} = \frac{K_n'}{2}\left(\frac{W}{L}\right)\left(V_{GS_2}-V_T\right)^2\left(1+\overset{\emptyset}{\cancel{\lambda}}\,V_{DS_2}\right)$$

$$= \frac{2.5e\text{-}5}{2}\left(V_{GS_2}-0.75\right)^2$$

$$5V - V_{DS_2} - I_{DS_2}R_3 + 5V = 0 \Rightarrow \text{does not help}$$

$$5V = V_{GS_2} + R_3 I_{DS_2} - 5V$$

$$I_{DS_2} = 12.5e\text{-}6\left(10V - R_3 I_{DS_2} - 0.75\right)^2 = 1.25e\text{-}5\left(9.25 - R_3 I_{DS_2}\right)^2$$

$$= 1.25e\text{-}5\left(9.25^2 - 18.5\, I_{DS_2} R_3 - R_3^2 I_{DS_2}^2\right)$$

$$= 0.001069 - 115.625\, I_{DS_2} - 3.125e6\, I_{DS_2}^2$$

$$3.125e6\left(I_{DS_2}\right)^2 + 116.625\, I_{DS_2} - 0.001069 = 0$$

$$I_{DS_2} = \frac{+116.625 \pm \sqrt{(116.625)^2 - 4(3.125e6)(0.001069)}}{2\,(3.125e6)}$$

$$= 21.1\,\mu A$$

or

$$\boxed{I_{DS_2} = 16.22\,\mu A}$$

$$V_{GS} = 10V - R_3 I_{DS_2} = -0.\cancel{55}V \text{ or } \boxed{1.89V}$$

Check assumption: $V_{DS} > V_{GS} - V_T$

$V_{DS} = V_{GS} \Rightarrow 0 > -0.75V$ ✓✓

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

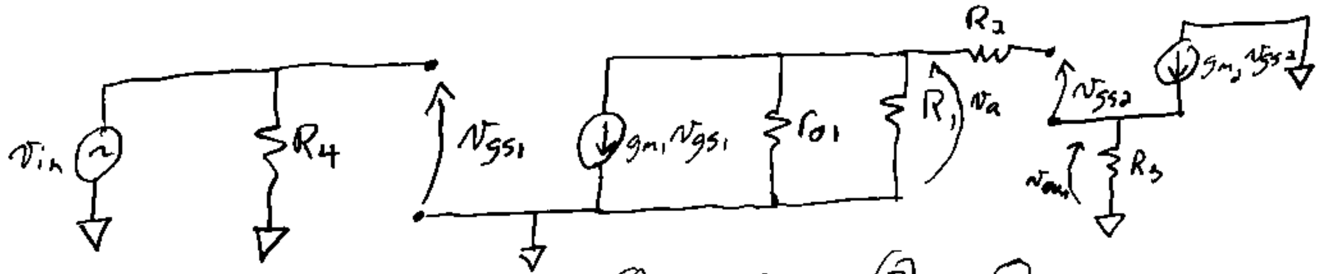
Conversion:

$$g_{m1} = \frac{51.25e\text{-}6}{\frac{0-(-2.0)}{2}} = 51.25e\text{-}6\ \Omega^{-1}$$

$$r_{o1} = \frac{\frac{1}{\lambda} + V_{DS_1}}{I_{DS_1}} = \frac{100+2.5}{51.25e6} = 2e6\ \Omega$$

$$g_{m2} = \frac{16.22\ uA}{\left(\frac{1.89-0.75}{2}\right)} = 28.45e\text{-}6\ \Omega^{-1}$$

$$r_{o2} = \infty \ (\text{since } \lambda = 0)$$



AC solution

$$A_v = \frac{v_{out}}{v_{in}} = \overset{①}{\frac{v_{out}}{v_{gs2}}} \overset{②}{\left(\frac{v_{gs2}}{v_a}\right)} \overset{③}{\left(\frac{v_a}{v_{gs1}}\right)} \overset{④}{\left(\frac{v_{gs1}}{v_{in}}\right)}$$

① $v_{out} = g_{m2} v_{gs2} R_3$

$$\frac{v_{out}}{v_{gs2}} = (28.45e\text{-}6)(500e3) = 14.225\ V/V$$

② $v_a = v_{gs2} + g_{m2} v_{gs2} R_3$

$$\frac{v_{gs2}}{v_a} = \frac{1}{1+g_{m2}R_3} = \frac{1}{1+(28.45e\text{-}6)(500e3)} = 0.06568$$

③ $v_a = -g_m v_{gs1}(r_{o1} \| R_1)$

$$\frac{v_a}{v_{gs_1}} = -g_{m1}(r_{o1} \| R_1) = -51.26e\text{-}6\,(2e6 \| 1e6)$$
$$= -34.1\overline{6}\ V/V$$

④ $v_{gs1} = v_{in}$

$$\frac{v_{gs1}}{v_{in}} = 1$$

$$A_v = (14.225)(0.06568)(-34.1\bar{6})(1)$$

$$\boxed{A_v = -31.9 \ V/V}$$