Name: PID:

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Electrical and Computer Engineering Department

ECE 65 – Fall 2019

Components and Circuits lab

Final Exam

Closed books, twenty-five double-sided cheat sheets, and calculators are allowed

Electronic devices are not allowed.

Please put all answers in the answer sheets.

Write your name and PID on all pages.

Please do not begin until told. Show your work. Good luck.

All electronic devices including cell phones must be turned off and stored away in a backpack or a purse. Anyone caught with such a device on their person during the exam will be charged with academic dishonesty.

You can use the back of every page as a **scratch** paper.

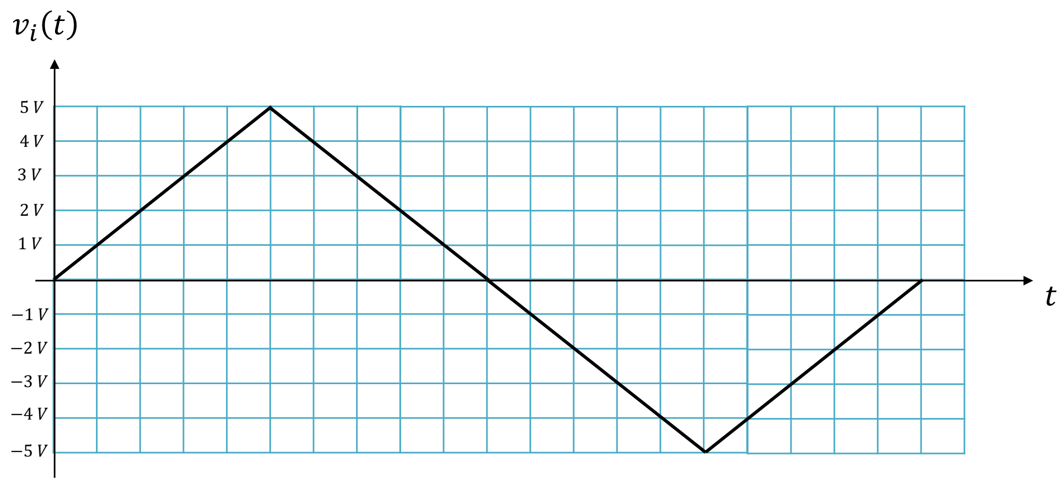
The main pages are numbered. If you remove the staple, you should order the pages and staple them before submitting your exam. **Do not remove or add any pages to your exam script.**

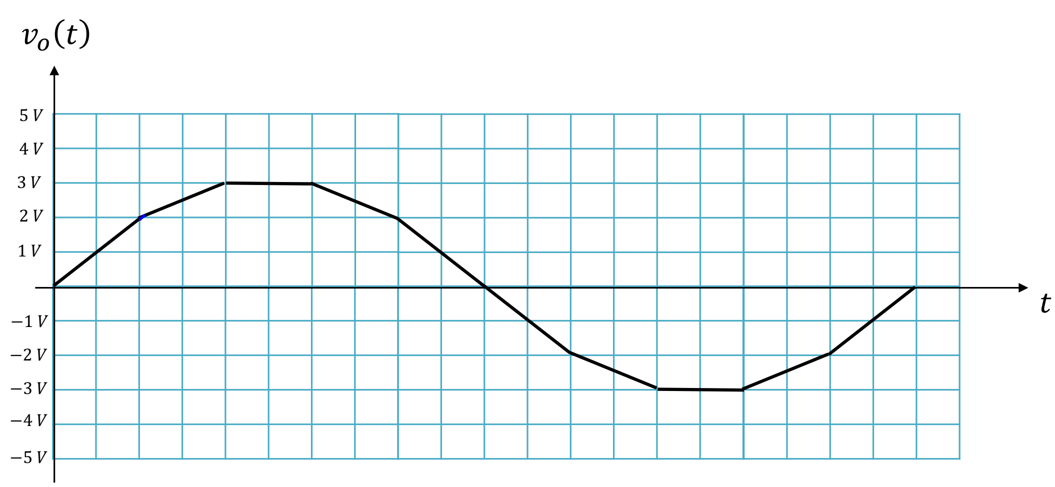
Name: PID:

Problem 1. (15 points)

a) Design a diode waveform shaping circuit that would produce the following output voltage waveform in response to the sketched input voltage waveform. You can use PN junction diodes with $V_{D0} = 0.7\ V$, DC voltage sources and resistors in your design. Make sure to include the input signal source and label the output terminals.

b) Parametrically solve your designed circuit. That means write the possible cases of the operation of the diode(s) in your designed circuit, and for each case, include the calculation of finding v_o and the range of v_i. **Write complete equations and show your work.**



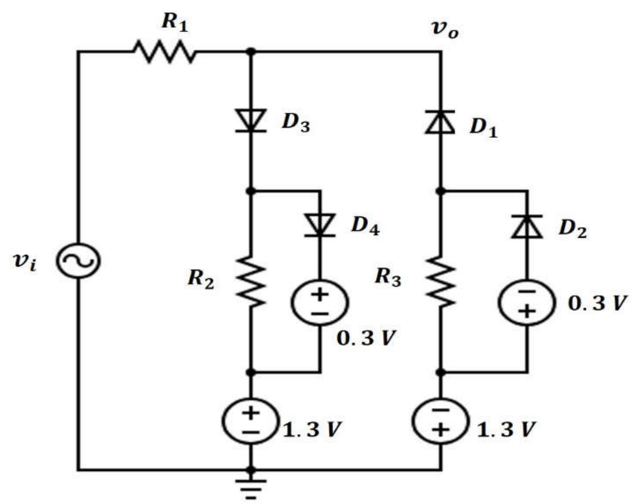


Problem 1

From the waveform, it can be written,

$$v_o = \begin{cases} -3; & -5 < v_i \leq -4 \\ \frac{v_i}{2} - 1; & -4 < v_i \leq -2 \\ v_i; & -2 < v_i \leq 2 \\ \frac{v_i}{2} + 1; & 2 < v_i \leq 4 \\ 3; & 4 < v_i \leq 5 \end{cases}$$

Designed circuit is shown below:



$$R_1 = R_2 = R_3 = 1k\Omega$$

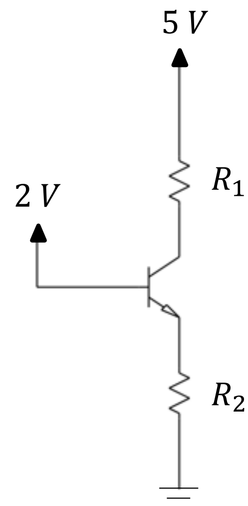
	D1	D2	D3	D4	Input voltage range	Output voltage, v_o
Case 1	√	√	×	×	$-5 < v_i \leq -4$	-3
Case 2	√	×	×	×	$-4 < v_i \leq -2$	$\frac{v_i R_3}{R_1 + R_3} - \frac{2R_1}{R_1 + R_3} = \frac{v_i}{2} - 1$
Case 3	×	×	×	×	$-2 < v_i \leq 2$	v_i
Case 4	×	×	×	√	$2 < v_i \leq 4$	$\frac{v_i R_2}{R_1 + R_2} + \frac{2R_1}{R_1 + R_2} = \frac{v_i}{2} + 1$
Case 5	×	×	√	√	$4 < v_i \leq 5$	3

Name: PID:

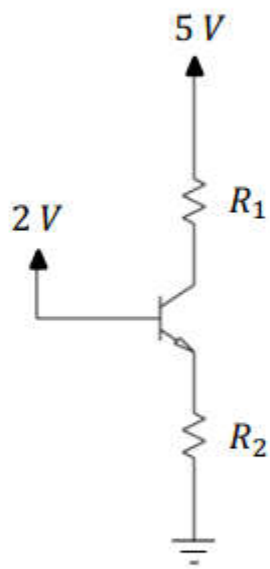
Problem 2. (6 points)

Design this BJT circuit to establish a collector current of $0.5\ mA$ and a reverse-bias voltage of 1V on the collector-base junction. Assume $\beta = 100, V_{D0} = 0.7V,\ \ V_{sat} = 0.2\ V$.

Show your work.



Problem 2



Since collector-base junction has 1V reverse bias. Then,

$$V_C = V_B + 1 = 3\ V$$

$$V_E = V_B - V_{Do} = 1.3\ V$$

Now, $V_{CE} = 1.7\ V > V_{Do} \Rightarrow Active\ mode \Rightarrow I_C = \beta I_B\ and\ I_E = (\beta + 1)I_B$. So,

$$R_1 = \frac{5 - V_C}{I_C} = 4\ k\Omega$$

$$\frac{I_C}{I_E} = \frac{\beta}{\beta + 1} = \frac{\frac{5 - V_C}{R_1}}{\frac{V_E}{R_2}} \Rightarrow R_2 = R_1 \frac{V_E}{5 - V_C} \frac{\beta}{\beta + 1} = 2.574\ k\Omega$$

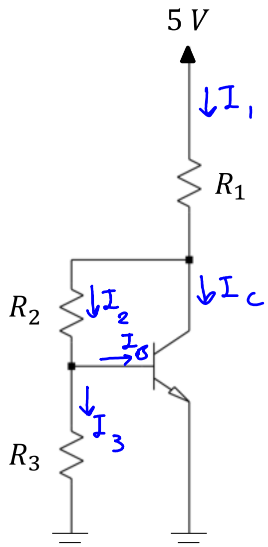
Name: PID:

Problem 3. (8 points)

Design the following circuit to establish $I_c = 2\ mA$, $I_{R_3} = 0.02\ mA$, and $V_c = 2.5\ V$.

Assume $\beta = 100$, $V_{D0} = 0.7V$, $V_{sat} = 0.2\ V$.

Show your work.



$I_3 = 0.02\,mA$

$I_C = 2\,mA > 0 \rightarrow$ BJT is ON

$\left\{ \begin{array}{l} V_C = 2.5\,V \\ V_E = 0V \end{array} \right. \Rightarrow V_{CE} = 2.5V > V_{D_0}$

BJT is in active mode

$\Downarrow$

$I_B = \dfrac{I_C}{\beta} = 0.02\,mA$

KCL at the Base node:

$I_2 = I_B + I_3 = 0.04\,mA$

KCL at the Collector node:

$I_1 = I_C + I_2 = 2\,mA + 0.04\,mA = 2.04\,mA$

Ohm's law: $R_1 = \dfrac{5V - V_C}{I_1} = \dfrac{5 - 2.5}{2.04\,mA} = 1.225\,k\Omega$

BJT is ON $\longrightarrow V_{BE} = 0.7\,V$, $V_E = 0 \Rightarrow V_B = 0.7\,V$

Ohm's law: $R_3 = \dfrac{V_B}{I_3} = \dfrac{0.7\,V}{0.02\,mA} = 35\,k\Omega$

Ohm's law: $R_2 = \dfrac{V_C - V_B}{I_2} = \dfrac{2.5 - 0.7}{0.04\,mA} = 45\,k\Omega$

$\boxed{R_1 = 1.225\,k\Omega}$, $\boxed{R_2 = 45\,k\Omega}$, $\boxed{R_3 = 35\,k\Omega}$

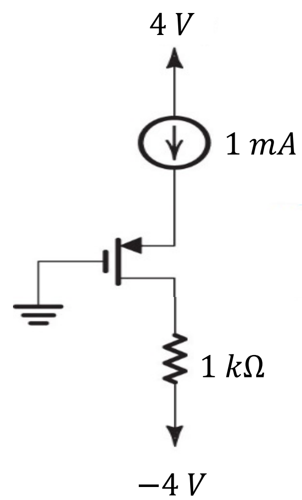
Name: PID:

Problem 4. (8 points)

In the following circuit the transistor has $|V_t| = 1\ V$, $\mu\, C_{ox}\frac{W}{L} = 2\ mA/V^2$, and $\lambda = 0$.

a) Find the node voltages at the source and drain.

b) Replace the current source with a resistor. Calculate the value of the resistor such that the current flowing through the resistor is equal to $1\ mA$.



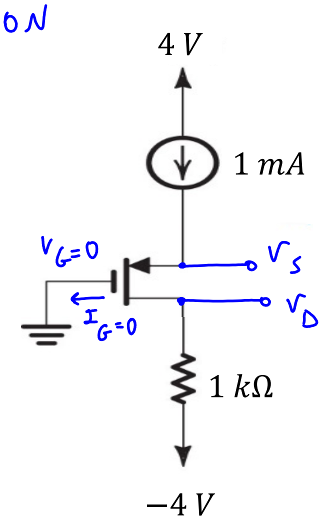
Name: PID:

Problem 4. (8 points)

In the following circuit the transistor has $|V_t| = 1\ V$, $\mu\, C_{ox}\frac{W}{L} = 2\ mA/V^2$, and $\lambda = 0$.

a) Find the node voltages at the source and drain.

b) Replace the current source with a resistor. Calculate the value of the resistor such that the current flowing through the resistor is equal to $1\ mA$.



$I_D = 1mA > 0 \longrightarrow$ MOSFET is ON

$V_D = I_D\, R_D - 4 = 1V - 4V = -3V$

$\boxed{V_D = -3V}$

$V_{DG} = V_D - V_G = -3 - 0 = -3V$

$V_{DG} = V_{SG} - V_{SD} = -3V$

$\Rightarrow V_{SD} = V_{SG} + 3V > V_{SG} - |V_{tp}|$

$\Rightarrow V_{SD} > V_{ov} \Rightarrow$ MOSFET is in Saturation

$I_D = \frac{1}{2} k_n V_{ov}^2 = \frac{1}{2} \times 2\left(mA/V^2\right) \times V_{ov}^2 \longrightarrow V_{ov}^2 = 1 \longrightarrow V_{ov} = 1$

$V_{SG} - |V_{tp}| = 1 \longrightarrow V_{SG} = 2V \longrightarrow V_S - V_G = 2V \longrightarrow \boxed{V_S = 2V}$

b) $R_S = \frac{4 - V_S}{I_D} = \frac{4 - 2}{1mA} = 2\,k\Omega \longrightarrow \boxed{R_S = 2\,k\Omega}$

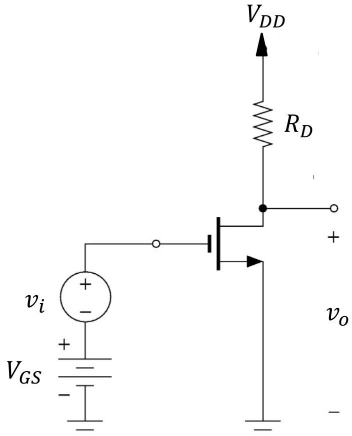
Name: PID:

Problem 5. (8 points)

In the following circuit, $V_{DD} = 5\ V, V_{OV} = 0.5\ V, k_n = 1\ mA/V^2$, and $\lambda = 0$. Complete the table. Neglect the effect of v_i on V_{OV}.

Note: $\hat{v}_o$ represents the maximum symmetrical signal swing allowed at the drain and $\hat{v}_i$ is the maximum allowable amplitude of the input signal.

Show your work.



V_{DS}	A_v	$\hat{v}_o$	$\hat{v}_i$	I_D	R_D
$1\ V$	$-16\ V/V$	$0.5\ V$	$31.25\ mV$	$125\ \mu A$	$32\ k\Omega$
$1.5\ V$	$-14\ V/V$	$1\ V$	$71.43\ mV$	$125\ \mu A$	$28\ k\Omega$
$2\ V$	$-12\ V/V$	$1.5\ V$	$125\ mV$	$125\ \mu A$	$24\ k\Omega$

$A_{v_o} = -g_m R_D \parallel r_o$, $r_o = \infty \longrightarrow A_{v_o} = -g_m R_D$

no load $\rightarrow A_v = A_{v_o}$

$$A_v = \frac{-2 I_D R_D}{V_{OV}} = -\frac{2(V_{DD} - V_{DS})}{V_{OV}} = \frac{-2(5 - V_{DS})}{0.5} = -4(5 - V_{DS}) \quad (V/V)$$

$\hat{v}_o = \min\{(V_{DS} - V_{OV}), (V_{DD} - V_{DS})\}$, in this problem: $\hat{v}_o = V_{DS} - V_{OV}$

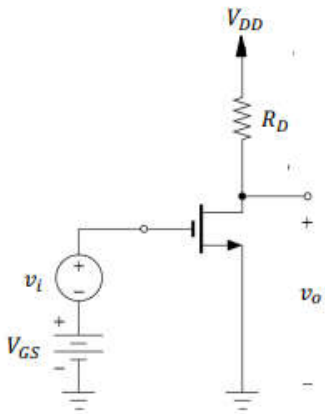
$$\hat{v}_i = \frac{\hat{v}_o}{A_v}$$

$I_D = \frac{1}{2} k_n V_{OV}^2 = 125\ \mu A$ the same for all V_{DS} values

$$R_D = \frac{V_{DD} - V_{DS}}{I_D} = \frac{5 - V_{DS}}{125\ \mu A} = 40 - 8 V_{DS}$$

The solution with considering the effect of vi on VOV

Problem 5



V_{DS}	A_v	$\hat{v}_o$	$\hat{v}_i$	I_D	R_D
$1\ V$					
$1.5\ V$					
$2\ V$					

Since $V_{OV} < V_{DS}$ for all cases, then MOS is in saturation for all three cases. Then,

$$I_D = 0.5 \times k_n V_{OV}^2 = 0.125\ mA$$

$$g_m = \frac{2I_D}{V_{OV}} = 0.5\frac{mA}{V}; \qquad r_o = \infty$$

Now,

$$R_D = \frac{V_{DD} - V_{DS}}{I_D}$$

From the input/output configuration, we can identify that this is an CS amplifier without source resistance. Then,

$$A_v = -g_m(R_D \parallel r_o) = -g_m R_D$$

In order keep the MOS in saturation, we need to satisfy the following relation,

$$0 < V_{OV} + v_{gs} < V_{DS} - v_{ds} \Rightarrow 0 < V_{OV} + v_i < V_{DS} - v_o \Rightarrow 0 < V_{OV} + v_i < V_{DS} - |A|v_i$$

In other words,

$$-V_{OV} < v_i < \frac{V_{DS} - V_{OV}}{1 + |A|}$$

Maximum input symmetrical signal swing, $\hat{v_i} = \min\left\{0.5, \frac{V_{DS}-V_{OV}}{1+|A|}\right\}$

Maximum input symmetrical signal swing, $\widehat{v_o} = A\ \hat{v_i}$

V_{DS}	A_v	$\widehat{v_o}$	$\hat{v_i}$	I_D	R_D
1 V	-16	$0.47\ V$	$29.4\ mV$	0.125 mA	$32\ k\Omega$
1.5 V	-14	$0.93\ V$	$66.67\ mV$	0.125 mA	$28\ k\Omega$
2 V	-12	$1.38V$	$115.3\ mV$	0.125 mA	$24\ k\Omega$

Name: PID:

Problem 6. (15 points)

Answer the following questions for the below MOSFET amplifier circuit. Assume capacitors are short in the signal circuit. Use $V_A = 100\ V$, $k_n = 4\ mA/V^2$, $V_t = 1\ V$, and Ignore the early effect in the bias circuit.

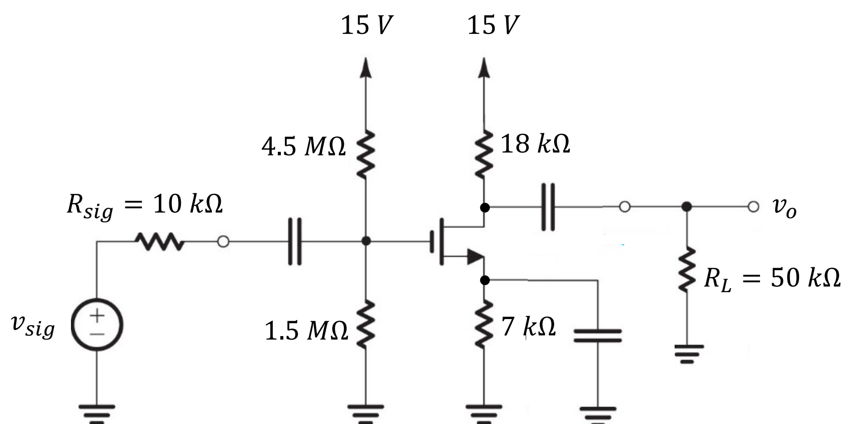
a) Find the Bias point of the amplifier circuit.

b) Find the small signal parameters of the amplifier.

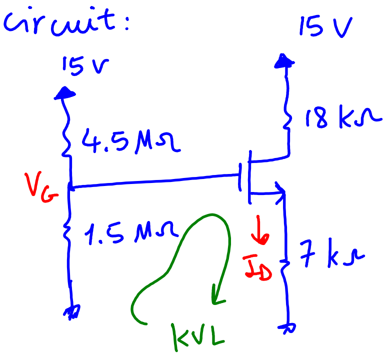
c) Draw the small signal equivalent circuit.

d) Find the open loop voltage gain (A_{vo}), voltage gain (A_v), total circuit voltage gain (A), input resistance (R_i), and output resistance (R_o) of this circuit.

e) If v_{sig} is a sine wave with peak amplitude of 5 mV, sketch the instantaneous current and voltages $i_D(t)$, $v_G(t)$, $v_D(t)$, $v_L(t)$, and $v_S(t)$.



a) Bias circuit:



$$V_G = \frac{1.5\ M\Omega}{1.5\ M\Omega + 4.5\ M\Omega} \times 15\ V = 3.75\ V$$

MOSFET is in saturation because it functions as an amplifier.

$$I_D = \frac{1}{2} k_n V_{ov}^2 = \frac{1}{2} \times 4\ (mA/V^2) \times V_{ov}^2$$

KVL : $V_G = V_{GS} + 7\ k\Omega \times I_D \longrightarrow \underbrace{V_G - V_t}_{3.75-1} = \underbrace{V_{GS} - V_t}_{V_{ov}} + 7\ k\Omega \times I_D$

Name: PID:

Problem 6.

$$\begin{cases} I_D = 2\left(\frac{mA}{V^2}\right) V_{ov}^2 \\ I_D = \dfrac{2.75 - V_{ov}}{7\,(k\Omega)} \end{cases} \longrightarrow 2.75 - V_{ov} = 14\left(\frac{1}{V}\right) \times V_{ov}^2$$

$$14\, V_{ov}^2 + V_{ov} - 2.75 = 0 \longrightarrow \begin{cases} V_{ov} \simeq 0.41\ V \ \checkmark \\ V_{ov} \simeq -0.48\ V \ \times \quad \text{MOSFET is ON} \end{cases}$$

$$\boxed{V_{ov} = 0.41\ V}$$

$$\boxed{I_D = 336\ \mu A}$$

$$V_{ov} = V_{GS} - V_t \longrightarrow \boxed{V_{GS} = 1.41\ V} \longrightarrow V_G - V_S = 1.41\ V \longrightarrow V_S = 3.75 - 1.41$$

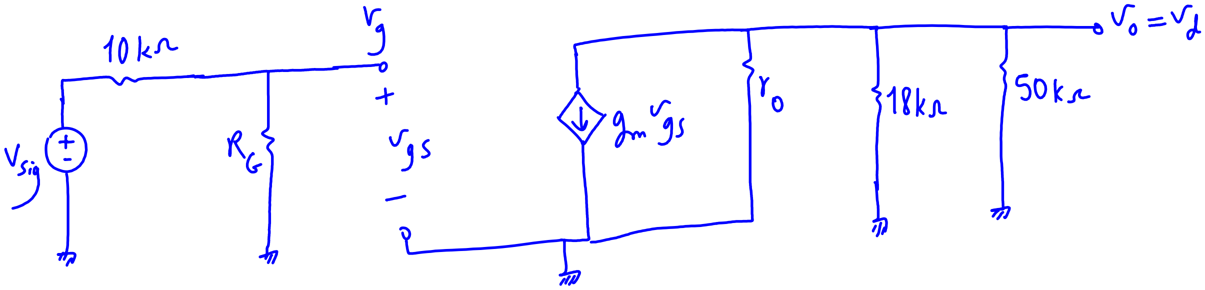
$$\boxed{V_S = 2.34\ V}$$

$$V_D = 15\,V - 18\,k\Omega \times I_D = 8.95\ V, \quad \boxed{V_D = 8.95\ V} \longrightarrow \boxed{V_{DS} = 6.61\ V}$$

b) $g_m = \dfrac{2 \times I_D}{V_{ov}} = 1.64\ mA/V$

$$r_o = \frac{1}{I_D \lambda} = \frac{V_A}{I_D} = \frac{100}{0.336} \simeq 298\ k\Omega$$

c)



$$R_G = 4.5\,M\Omega \,\|\, 1.5\,M\Omega = 1.125\ M\Omega$$

Name: PID:

Problem 6.

d) Common source amplifier :

$R_G = 1.125\ M\Omega$

$A_{v_o} = -g_m (R_D \parallel r_o) = -1.64\ (mA/V)\ (18k\Omega \parallel 298\ k\Omega) \simeq 27.84\ V/V$

$R_o = R_D \parallel r_o = 16.97\ k\Omega$

$R_i = R_G = 1.125\ M\Omega$

$$A_v = \frac{R_L}{R_L + R_o} A_{v_o} = -\frac{50\ k\Omega}{50k\Omega + 16.97k\Omega} \times 27.84 = -20.78\ V/V$$

$$A = \frac{v_o}{v_{sig}} = \frac{R_i}{R_i + R_{sig}} A_v = \frac{1.125\ M\Omega}{1.125\ M\Omega + 0.01\ M\Omega} \times (-20.78) = -20.6\ V/V$$

e) $v_{sig} = 5 \sin \omega t\ \ (mV)$

$v_G(t) = V_G + v_g(t)$

from the signal circuit : $v_g = \dfrac{R_G}{R_G + R_{sig}} \times v_{sig} = 4.96 \sin \omega t\ \ (mV)$

$v_G(t) = 3.75\ (V) + 4.96\ (mV) \sin \omega t$

$v_D(t) = V_D + v_d(t)$

$$v_d = v_o = v_{load}\ ,\quad v_o = -g_m v_{gs} (R_L \parallel R_D \parallel r_o) = -g_m \underbrace{\left(\frac{R_G}{R_G + R_{sig}} \times v_{sig}\right)}_{v_{gs} \text{ or } v_g} \underbrace{(R_L \parallel R_D \parallel r_o)}_{12.67\ k\Omega}$$

Name: PID:

Problem 6.

$v_d = v_0 = -103.03\ (mV)\ \sin \omega t$

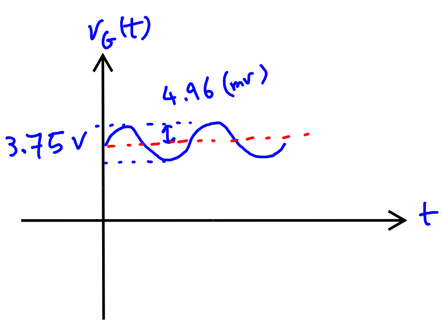
$v_D(t) = 8.95\ (V) + (-103.03)\ (mV)\ \sin \omega t$

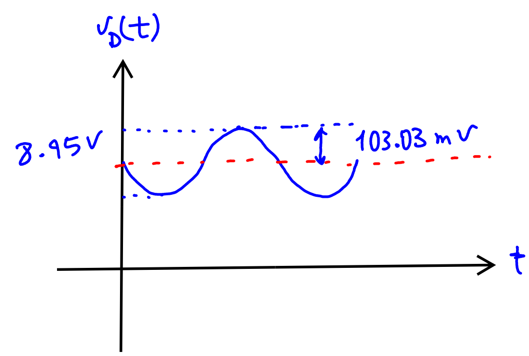
$v_L(t) = v_d(t) = -103.03\ (mV)\ \sin \omega t$

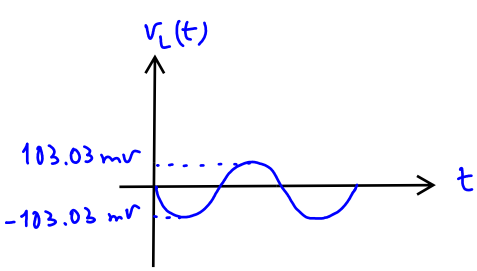
$v_S(t) = V_S + v_s(t) = 2.34\ (V) + 0 = 2.34\ (V)$

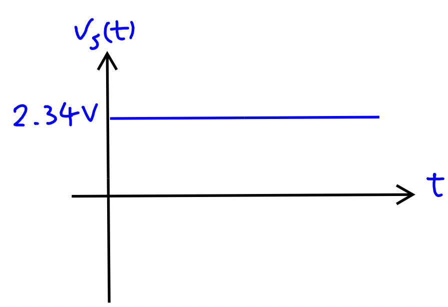
$i_D(t) = I_D + i_d(t)$

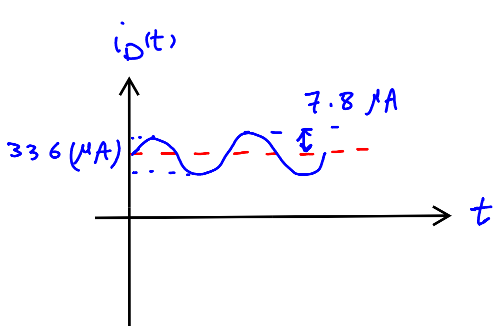
$i_d = \dfrac{-v_0}{\underbrace{R_D \| R_L}_{13.23\,k\Omega}} = 7.8\ (\mu A)\ \sin \omega t \longrightarrow i_D(t) = 336\,(\mu A) + 7.8\ (\mu A)\ \sin \omega t$



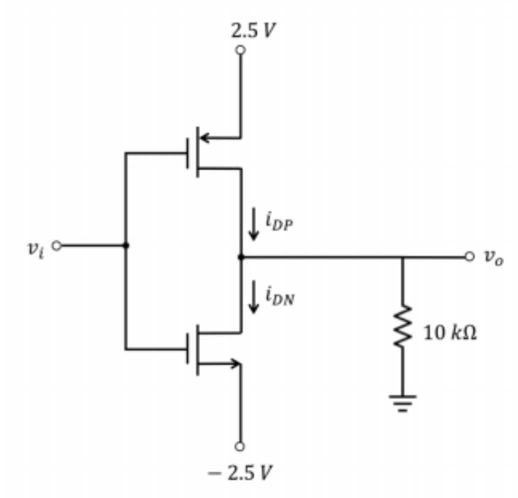








Problem 7



$$v_I = 2.5\ V \Rightarrow V_{OV,P} < 0\ and\ V_{OV,N} > 0 \Rightarrow NMOS\ ON, PMOS\ OFF$$

$$i_{DP} = 0$$

Assuming NMOS in Triode,

$$k_n\left[V_{OV,N}(v_o + 2.5) + \frac{1}{2}(v_o + 2.5)^2\right] = \frac{-v_o}{10k}$$

$$\Rightarrow 10\left[4(v_o + 2.5) + \frac{1}{2}(v_o + 2.5)^2\right] + (v_o + 2.5) - 2.5 = 0$$

$$\Rightarrow v_o = -2.44\ V$$

Now,

$$V_{OV,N} = 4 > v_o + 2.5 \Rightarrow Correct\ Assumption$$

Then,

$$i_{DN} = \frac{v_o}{10k} = 0.244\ mA$$