The transistors in this homework are to be implemented in 0.18 µm MOS technology so all dimensions must be a multiple of these numbers (we will approximate 5.04 as 5).

1. For the basic transistor circuit in Fig. 1, solve for the Q-point (all three currents and voltages on the transistor) assuming a V_{TNO} =+0.5V, $K_n'=\mu_n C_{ox}$=100 µA/V^2, W=5µm, L=0.18µm, a channel length modulation parameter, λ=0.0 V^{-1}, a body effect parameter, γ=0.0 V$^{1/2}$ and φ_F=0.4V.
   a. Assuming the transistor is biased in cutoff (neglect leakage currents).
   b. Assuming the transistor is biased in triode/linear.
   c. Assuming the transistor is biased in saturation.
   d. Which assumption is valid?

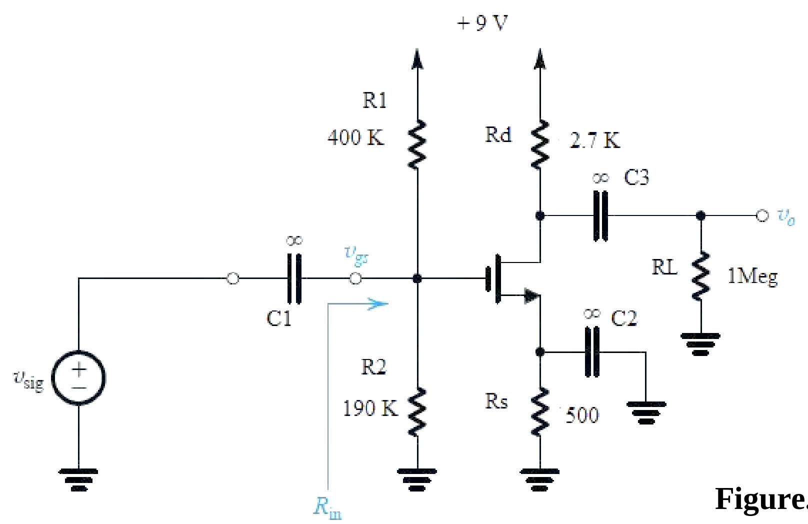


Figure. 1

   e. Repeat part c for λ=0.1 V^{-1} .
   f. For λ=0.1 V^{-1}, (part e answers) determine the voltage gain v_o/v_{sig}
   g. What is the maximum allowable v_o signal swing without distortion.

Solution:

Given, $V_{TN} = 0.5$ V, $k_n' = \mu_n C_{ox} = 100$ µA/V^2, $\frac{W}{L} = 28$

(a) Assuming transistor in cut-off region,

$I_D = 0,$

$V_D = 9$ V,

$V_G = (9\text{ V}) \times \frac{190\text{k}}{190\text{k}+400\text{k}} = 2.9$ V,

$V_S = 0$

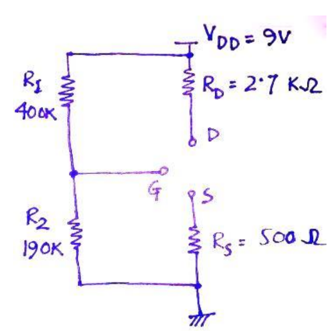
$V_{GS} = 2.9$ V

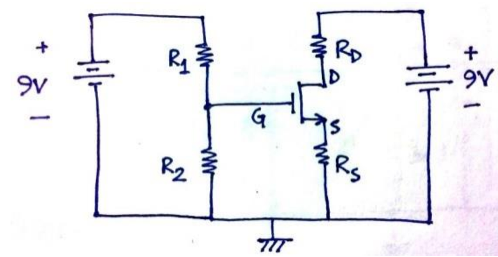
$V_{DS} = 9.0$ V

Q-point = (0 A, 9.0 V)

Here, $V_{DS} > V_{GS} - V_T$

So, assumption not valid.



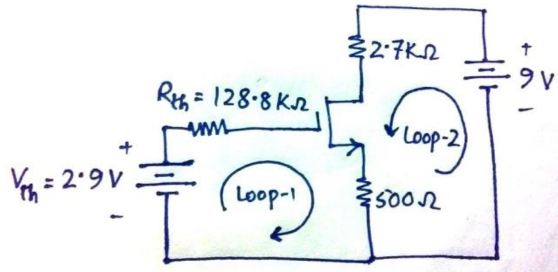


(b) Assuming transistor in triode region,

We calculate Thevenin equivalent circuit on the gate side.

$V_{th} = (9\text{ V}) \times \frac{190\text{k}}{190\text{k}+400\text{k}} = 2.9\text{ V}$

$R_{th} = R_1 \parallel R_2 = 400\text{k}\Omega \parallel 190\text{k}\Omega = 128.8\text{k}\Omega$



Applying KVL in loop-1, $V_{th} = V_{GS} + I_D R_S$

KVL in loop-2, $V_{DD} = I_D R_D + V_{DS} + I_D R_S$

For triode region, $I_D = k_n' \left(\frac{W}{L}\right)\left[(V_{GS} - V_{TN})V_{DS} + \frac{V_{DS}^2}{2}\right]$

Using loop-1 to solve for $V_{GS} = V_{th} - I_D R_S$**.**

From loop-2 eq., we get, $V_{DS} = V_{DD} - I_D(R_D + R_S)$**.**

Plugging these expressions into triode current equation,

$$I_D = k_n' \left(\frac{W}{L}\right)\left[(V_{th} - I_D R_S - V_{TN})\left(V_{DD} - I_D(R_D + R_S)\right) + \frac{\left(V_{DD} - I_D(R_D + R_S)\right)^2}{2}\right]$$

$$= k_n' \left(\frac{W}{L}\right)\left[\left(2.4 - I_D(500\Omega)\right)\left(9.0 - I_D(3.2\text{k}\Omega)\right) + \frac{\left(9.0 - I_D(3.2\text{k}\Omega)\right)^2}{2}\right]$$

$$= \left(2.8 \times 10^{-3}\frac{\text{A}}{\text{V}^2}\right)\left[(6.72 \times 10^7 \Omega^2)I_D^2 - (4.098 \times 10^4\text{ V.}\Omega)I_D + 62.1\text{ V}^2\right]$$

$$= (1.8816 \times 10^5\text{ A}^{-1})I_D^2 - 114.7 I_D + 0.1739\text{ A}$$

$$\Rightarrow 0 = (1.8816 \times 10^5\text{ A}^{-1})I_D^2 - 115.7 I_D + 0.1739\text{ A}$$

$$\Rightarrow 0 = I_D^2 - 6.149 \times 10^{-4} I_D + 9.242 \times 10^{-7}\text{ A}$$

$$\Rightarrow I_D = \frac{6.149 \times 10^{-4} \pm \sqrt{(6.149 \times 10^{-4})^2 - 4 \times 9.242 \times 10^{-7}}}{2}$$

I_D = imaginary number

Assumption not valid

(c) Assuming transistor in saturation region,

Same equivalent circuit and loop equations as triode region.

$$V_{GS} = V_{th} - I_D R_S$$

$$V_{DS} = V_{DD} - I_D(R_D + R_S)$$

Saturation current, $I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{GS} - V_{TN})^2\right]$

Plugging the voltages into current equation,

$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{th} - I_D R_S - V_{TN})^2\right]$$

$$= \left(1.4 \times 10^{-3}\,\frac{\text{A}}{\text{V}^2}\right)\left(2.4\text{ V} - I_D(500\ \Omega)\right)^2$$

$$= \left(1.4 \times 10^{-3}\,\frac{\text{A}}{\text{V}^2}\right)\left(5.76\text{ V}^2 - (2.4 \times 10^3\text{ V}.\Omega)I_D + (2.5 \times 10^5\ \Omega^2){I_D}^2\right)$$

$$= (350\text{ A}^{-1}){I_D}^2 - 3.36 I_D + (8.064 \times 10^{-3})\text{ A}$$

$$\Rightarrow 0 = (350\text{ A}^{-1}){I_D}^2 - 4.36 I_D + (8.064 \times 10^{-3})\text{ A}$$

$$\Rightarrow 0 = {I_D}^2 - (1.246 \times 10^{-2}\text{ A})I_D + (2.304 \times 10^{-5}\text{ A}^2)$$

$$I_D = \frac{1.246 \times 10^{-2} \pm \sqrt{(1.246 \times 10^{-2})^2 - 4 \times 2.304 \times 10^{-5}}}{2}$$

$$I_D = 6.23 \pm 3.97\text{ mA} = 10.2\text{ or }2.26\text{ mA}$$

If $I_D = 10.2$ **mA,**

$V_{DS} = 9.0 - (10.2\text{ mA}) \times (3.2\text{ k}\Omega) = -23.64\text{ V}$

$V_{GS} = 2.9 - (10.2\text{ mA}) \times (500\ \Omega) = -2.2\text{ V}$

Here, $V_{DS} < V_{GS} - V_T$

Assumption not valid.

If $I_D = 2.26$ **mA,**

$V_{DS} = 9.0 - (2.26\text{ mA}) \times (3.2\text{ k}\Omega) = 1.77\text{ V}$

$V_{GS} = 2.9 - (2.26\text{ mA}) \times (500\ \Omega) = 1.77\text{ V}$

Here, $V_{DS} > V_{GS} - V_T$

Assumption valid.

The Q-point = (2.26 mA, 1.77 V)

(d) Saturation is the valid assumption.

(e) Given, $\lambda = 0.1\ \mathrm{V}^{-1}$

Saturation current is given by,

$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{GS} - V_{TN})^2\right](1 + \lambda V_{DS})$$

Plugging V_{DS} and V_{GS} into the equation,

$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{th} - I_D R_S - V_{TN})^2\right]\Big(1 + \lambda\big(V_{DD} - I_D(R_D + R_S)\big)\Big)$$

$$= \Big(\big(350\ \mathrm{A}^{-1}\big)I_D{}^2 - 3.36 I_D + \big(8.064 \times 10^{-3}\big)\ \mathrm{A}\Big)\big(1 + 0.9 - \big(320\ A^{-1}\big)I_D\big)$$

$$= \big(1.532 \times 10^{-2}\ \mathrm{A}\big) - 6.384\ I_D + \big(665\ A^{-1}\big)I_D{}^2 - 2.580 I_D + \big(1.075 \times 10^3\ \mathrm{A}^{-1}\big)I_D{}^2 - \big(1.12 \times 10^5\ \mathrm{A}^{-2}\big)\ I_D{}^3$$

$$\Rightarrow 0 = -\big(1.12 \times 10^5\ \mathrm{A}^{-2}\big)\ I_D{}^3 + \big(1.740 \times 10^3\ \mathrm{A}^{-1}\big)I_D{}^2 - 9.964\ I_D + \big(1.532 \times 10^{-2}\ \mathrm{A}\big)$$

$$\Rightarrow 0 = I_D{}^3 + \big(1.554 \times 10^{-2}\ \mathrm{A}\big)I_D{}^2 - \big(8.896 \times 10^{-5}\ \mathrm{A}^2\big)\ I_D + \big(1.368 \times 10^{-7}\ \mathrm{A}^3\big)$$

$$\Rightarrow 0 = I_D{}^3 + pI_D{}^2 + qI_D + r$$

Let,

$$a = \frac{1}{3}\big(3q - p^2\big) = 8.463 \times 10^{-6}\ \mathrm{A}^2$$

$$b = \frac{1}{27}\big(2p^3 - 9pq + 27r\big) = 4.606 \times 10^{-8}\ \mathrm{A}^3$$

$$A = \sqrt[3]{-\frac{b}{2} + \sqrt{\frac{b^2}{4} + \frac{a^3}{27}}} = 7.844 \times 10^{-4}\ \mathrm{A}$$

$$B = -\sqrt[3]{\frac{b}{2} + \sqrt{\frac{b^2}{4} + \frac{a^3}{27}}} = -3.596 \times 10^{-3}\ \mathrm{A}$$

$$X = A + B = -\,2.812 \times 10^{-3}\ \mathrm{A}$$

Or, $X = -\frac{A+B}{2} \pm \frac{A+B}{2}\sqrt{-3}$ = gives complex number.

Using real root only,

$$I_D = X - \frac{p}{3} = 2.368\ \text{mA}$$

$$V_{DS} = 9.0 - (2.368\ \text{mA}) \times (3.2\ \text{k}\Omega) = 1.422\ \text{V}$$

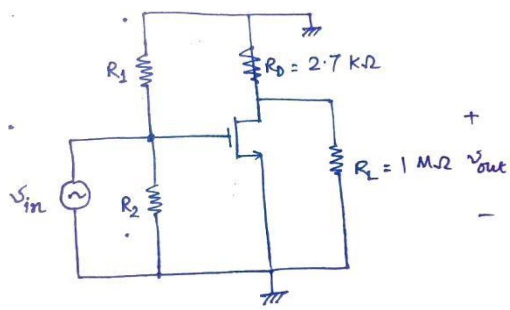
$$V_{GS} = 2.9 - (2.368\ \text{mA}) \times (500\ \Omega) = 1.716\ \text{V}$$

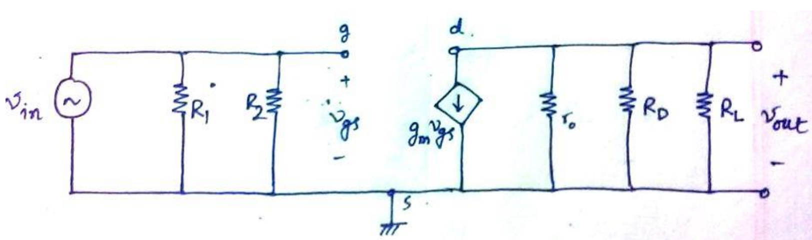
$$\text{So}, V_{DS} > V_{GS} - V_T$$

Q-point: (2.368 mA, 1.422 V).

Saturation assumption valid.

(f)





Using the equivalent small signal π-model,

$$g_m = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2 \times 2.368\ \text{mA}}{1.216\ \text{V}} = 3.895\ \text{mS}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS}}{I_D} = \frac{10\ \text{V} + 1.422\ \text{V}}{2.368\ \text{mA}} = 4.823\ \text{k}\Omega$$

Here, $v_{gs} = v_{in}$

$v_{out} = -g_m v_{gs}(r_o \parallel R_D \parallel R_L) = -g_m v_{in}(r_o \parallel R_D \parallel R_L)$

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

$A_v = -(3.895\ \text{mS})(1.728\ \text{k}\Omega) = -6.73\ \text{V/V}$

$$A_v = -6.73\ \text{V/V}$$

(g) To remain in small signal mode,

$v_{DS} \geq v_{GS} - V_{TN}$

$\Rightarrow V_{DS} - 6.73 v_{gs.\max} > V_{GS} + v_{gs.\max} - V_{TN}$

$\Rightarrow V_{DS} - V_{GS} + V_{TN} > 7.73 v_{gs.\max}$

$\Rightarrow \ v_{gs.\max} < 27 \text{ mV}$

Maximum V_{out} DC swing = 6.73$v_{gs.\max}$ = 179 mV

2. For the circuits shown in Fig. 2, find the labeled node voltages. The NMOS transistors have V_t = 1 V and $k_n{}'(W/L)$= 5 mA/V^2.

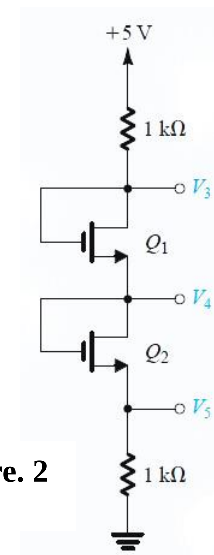


Figure. 2

Solution:

Here the NMOS transistors have their G and S tied together, that means, $V_{DS} = V_{GS}$
So, for both transistors,

$$V_{DS} > V_{GS} - V_t$$

Now, all the components are in series, hence

$$\frac{5 - V_3}{1k} = \frac{V_5}{1k}$$

$$\Rightarrow V_5 = 5 - V_3 \qquad (1)$$

For Transistor Q1,

$$I_D = \frac{V_5}{1k} = \frac{1}{2} 5\text{m}(V_3 - V_4 - 1)^2$$
$$\Rightarrow V_5 = 2.5(V_3 - V_4 - 1)^2 \qquad (2)$$

For Transistor Q2,

$$I_D = \frac{V_5}{1k} = \frac{1}{2} 5\text{m}(V_4 - V_5 - 1)^2$$
$$\Rightarrow V_5 = 2.5(V_4 - V_5 - 1)^2 \qquad (3)$$

From eq. (2) and (3), we get,

$$(V_3 - V_4 - 1)^2 = (V_4 - V_5 - 1)^2$$
$$\Rightarrow V_5 = 2V_4 - V_3 \qquad (4)$$

From eq. (1) and (4), we get,

$$5 - V_3 = 2V_4 - V_3$$
$$\Rightarrow \ V_4 = 2.5\ \text{V}$$

Now using this value in eq. (3),

$$V_5 = 2.5(1.5 - V_5)^2$$
$$\Rightarrow V_5{}^2 - 3.4V_5 + 2.25 = 0$$
$$\Rightarrow V_5 = \frac{3.4 \pm \sqrt{3.4^2 - 4 \times 2.25}}{2}$$
$$\Rightarrow V_5 = \frac{3.4 \pm 1.6}{2} = 2.5\ \text{V or } 0.9\ \text{V}$$

As $V_5 < V_4$, we can discard 2.5 V from the solution. So,

$$V_5 = 0.9\ \text{V}$$

Using this value in eq. (1),

$$V_3 = 5 - V_5 = 5 - 0.9 = 4.1\ \text{V}$$

The node voltages are,

$$V_3 = 4.1\ \text{V}$$
$$V_4 = 2.5\ \text{V}$$
$$V_5 = 0.9\ \text{V}$$

3. For the circuit below,
   a) Calculate the voltage gain. This configuration uses a current source as a load instead of the resistor, Rd.
   b) Why is the body of the PMOS transistor tied to the source/highest potential?
   c) If the PMOS transistor could be made with arbitrary dimensions such that W/L=2.81, what would be the new gain?
   d) Given the dimensions must be a multiple of 0.18 μm, how could we best approximate this value so as to get the benefits of the higher gain you should have found in part c but stay within the limits of the 0.18 μm technology?
   In an integrated circuit, this transistor load (or "active" load as opposed to the "passive" resistor load) results in huge space savings making complex analog circuits very compact and thus cheaper and higher performance.

   For M1, V_{TNO} =+0.5V, $K_n{}'=\mu_n C_{ox}$=100 μA/V^2 , W=5μm, L=0.18μm, a channel length modulation parameter, λ=0.0 V^{-1}, a body effect parameter, γ=0.0 $V^{1/2}$ and φ_F=0.4V.

   For M2, V_{TPO} =+4V, $K_p{}'=\mu_n C_{ox}$=100 μA/V^2 , W=0.54 μm, L=0.18 μm, a channel length modulation parameter, λ=0.0 V^{-1}, a body effect parameter, γ=0.0 $V^{1/2}$ and φ_F=0.4V.

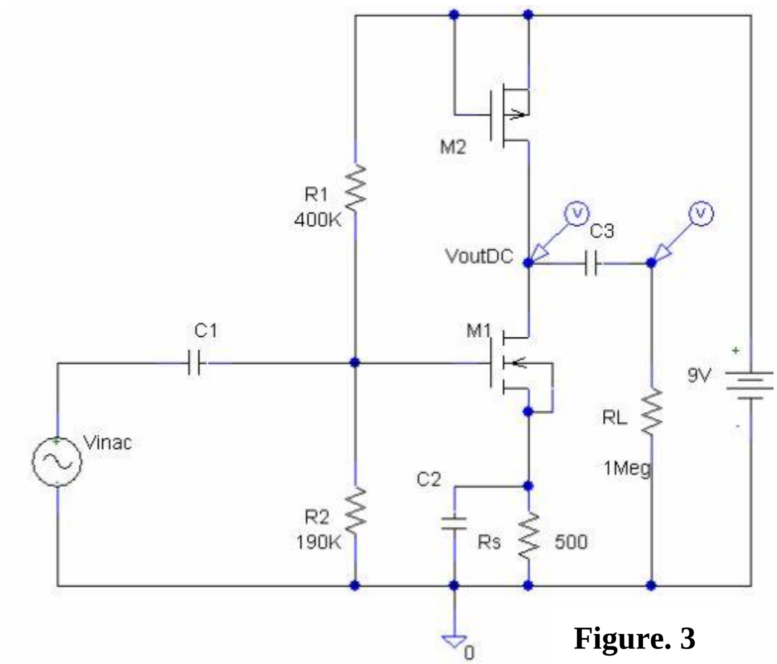
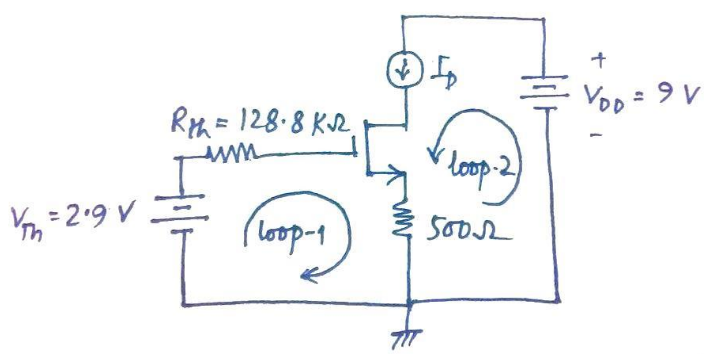


Figure. 3

Solution:

For a p-MOSFET like M2, the transistor is on if $V_{GS} \leq V_{TP}$. Since the gate is tied to the source, $V_{GS} = 0$ V, which will always be less than $V_{TP} = +4$ V. M2 is on and acts as a current source with I_D still a function of M1 Q-point.

(a) DC equivalent circuit is given by,



Assuming M2 is saturation region,

$$I_D = \frac{k'_p}{2}\left(\frac{W}{L}\right)\left[(V_{SG2} - |V_{TP}|)^2\right] = \frac{100\ \mu}{2} \times 3 \times 4^2 = 2.4\ \text{mA}$$

Assuming M1 in saturation region,

$$\text{KVL @Loop1}: V_{GS1} = V_{th} - I_D R_S$$

$$\text{KVL @Loop2}: V_{DS1} = V_{DD} - V_{SD2} - I_D R_S$$

$$\text{Saturation current,} \quad I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{GS1} - V_{TN})^2\right]$$

Plugging the voltages into current equation,

$$I_D = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{th} - I_D R_S - V_{TN})^2\right]$$

$$= \left(1.4 \times 10^{-3}\,\frac{\text{A}}{\text{V}^2}\right)\left(2.4\text{ V} - I_D(500\ \Omega)\right)^2$$

$$= \left(1.4 \times 10^{-3}\,\frac{\text{A}}{\text{V}^2}\right)\left(5.76\text{ V}^2 - (2.4 \times 10^3\text{ V}.\Omega)I_D + (2.5 \times 10^5\ \Omega^2){I_D}^2\right)$$

$$= (350\text{ A}^{-1}){I_D}^2 - 3.36 I_D + (8.064 \times 10^{-3})\text{ A}$$

$$\Rightarrow 0 = (350\text{ A}^{-1}){I_D}^2 - 4.36 I_D + (8.064 \times 10^{-3})\text{ A}$$

$$\Rightarrow 0 = {I_D}^2 - (1.246 \times 10^{-2}\text{ A})I_D + (2.304 \times 10^{-5}\text{ A}^2)$$

$$I_D = \frac{1.246 \times 10^{-2} \pm \sqrt{(1.246 \times 10^{-2})^2 - 4 \times 2.304 \times 10^{-5}}}{2}$$

$$I_D = 6.23 \pm 3.97\text{ mA} = 10.2\text{ or }2.26\text{ mA}$$

If $I_D = 2.26$ mA,

$V_{DS1} = 9.0 - V_{SD2} - (2.26\text{ mA}) \times (500\ \Omega)$

Saturation current of M1 and M2 must be equal. We also need to solve for V_{SD2}.

We need to incorporate Early effect into account. Let, $\lambda_{M1} = 0.1\text{ V}^{-1}$

Saturation current in the series branch, $I_D = 2.4$ mA

Saturation current equation for M1 then changes into,

$I_D = 2.4\text{ mA} = \frac{k_n'}{2}\left(\frac{W}{L}\right)\left[(V_{th} - I_D R_S - V_{TN})^2\right](1 + \lambda V_{DS1})$

$\Rightarrow 2.4\text{ mA} = \frac{100\ \mu}{2} \times 28 \times (2.4 - 2.4\text{mA} \times 500\Omega)^2(1 + \lambda V_{DS1})$

$\Rightarrow 2.4\text{ mA} = 2.016\text{ mA}(1 + \lambda V_{DS1})$

$\Rightarrow (1 + \lambda V_{DS1}) = 1.19$

$\Rightarrow \lambda V_{DS1} = 0.19$

$\therefore\ V_{DS1} = 1.9\ \mathrm{V}$

Now,

$V_{DS1} > V_{GS1} - V_{TN} = 1.2\ \mathrm{V}$, **so M1 is in saturation.**

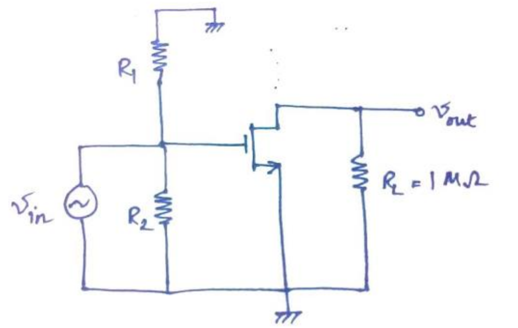
Performing KVL in loop-2,

$V_{SD2} = V_{DD} - V_{DS1} - I_D R_S = 9 - 1.9 - 1.2\ \mathrm{V} = 5.9\ \mathrm{V}$

Here,

$V_{SD2} > V_{SG2} - |V_{TP}|$, **so M2 is in saturation.**

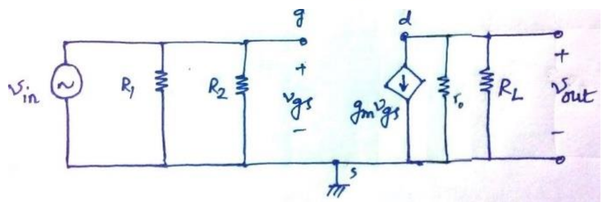
The Q-point = (2.4 mA, 1.9 V)



Small-signal parameters,

$$g_m = \frac{2I_D}{V_{GS1} - V_{TN}} = \frac{2 \times 2.4\ \mathrm{mA}}{1.2\ \mathrm{V}} = 4\ \mathrm{mS}$$

$$r_o = \frac{\frac{1}{\lambda} + V_{DS1}}{I_D} = \frac{10 + 1.9\ \mathrm{V}}{2.4\ \mathrm{mA}} = 4.96\ \mathrm{k\Omega}$$



Here, $v_{gs1} = v_{in}$

$v_{out} = -g_m v_{gs1}(R_L || r_o) = -g_m v_{in}(R_L || r_o)$

$A_v = -g_m(R_L || r_o) = -(4\ \mathrm{mS})(4.935\ \mathrm{k\Omega}) = -19.74\ \mathrm{V/V}$

$$A_v = -19.74\ \mathrm{V/V}$$

(b) We tie the bulk/body and source terminal together to eliminate the drifting of the expected V_{TP}.

(c) Here,

$$\left(\frac{W}{L}\right)_{M2} = 2.81$$

$$\left(\frac{W}{L}\right)_{M1} = 28$$

Now,

$$V_{GS1} = V_{TN} + V_{TP}\sqrt{\frac{\left(\frac{W}{L}\right)_{M2}}{\left(\frac{W}{L}\right)_{M1}}}$$

$$= 0.5 + 4\sqrt{\frac{2.81}{28}} = 1.77\ \text{V}$$

So,

$$g_{m1} = \frac{2I_D}{V_{GS} - V_{TN}} = \frac{2 \times 2.4\ \text{mA}}{1.27\ \text{V}} = 3.78\ \text{mS}$$

$$A_v = -g_m(R_L||r_o) = -(3.78\ \text{mS})(4.935\ \text{k}\Omega) = -18.67\ \text{V/V}$$

$$A_v = -18.67\ \text{V/V}$$

(d) The ratio of (W/L) of the transistors ≈ 10. To take the advantage of this higher gain, one should make $W_{M1} = 10W_{M2}$, and keep the gate lengths as low as possible.

4. Figure 4 shows a discrete-circuit amplifier. The input signal v_{sig} is coupled to the gate through a very large capacitor (shown as infinite). The transistor source is connected to ground at signal frequencies via a very large capacitor (shown as infinite). The output voltage signal that develops at the drain is coupled to a load resistance via a very large capacitor (shown as infinite).

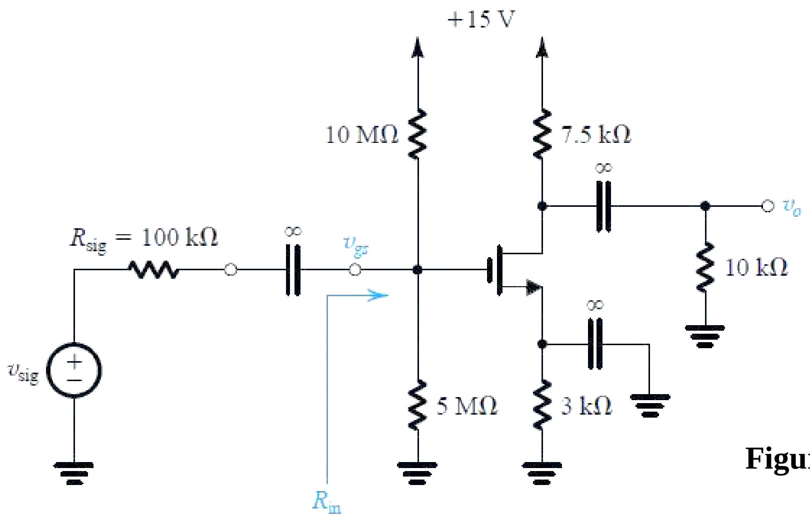


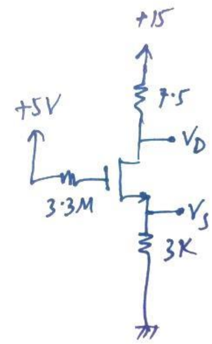
Figure. 4

a. If the transistor has $V_t = 1$ V, and $k_n'(W/L) = 2$ mA/V², verify that the bias circuit establishes V_{GS} = 2 V, $I_D = 1$ mA, and $V_D = +7.5$ V. That is, assume these values, and verify that they are consistent with the values of the circuit components and the device parameters.

b. Find g_m and r_o if $V_A = 100$ V.

c. Draw a complete small-signal equivalent circuit for the amplifier, assuming all capacitors behave as short circuits at signal frequencies.
d. Find R_{in}, v_{gs}/v_{sig}, v_o/v_{gs}, and v_o/v_{sig}.

Solution:
(a) DC equivalent circuit:



Here,

$$V_S = I_D \times 3\text{ k}\Omega = 1\text{ mA} \times 3\text{ k}\Omega = 3\text{ V}$$
$$V_D = 15 - I_D \times 7.5\text{ k}\Omega = 15 - 1\text{ mA} \times 7.5\text{ k}\Omega = 7.5\text{ V}$$

We can calculate,

$$V_{DS} = 7.5 - 3 = 4\text{ V}$$
$$V_{GS} = 5 - 3 = 2\text{ V} > V_t$$

So, the transistor is in saturation region.
Now saturation current,

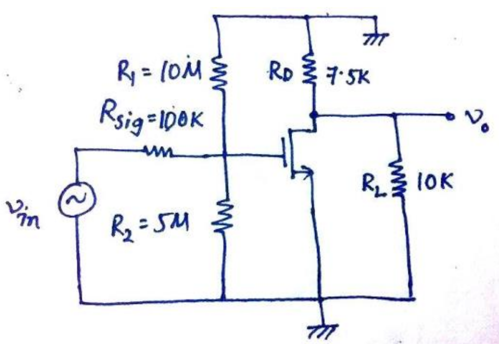
$$I_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(V_{GS} - V_t)^2 = \frac{1}{2} \times 2 \times (2-1)^2 = 1\text{ mA}$$

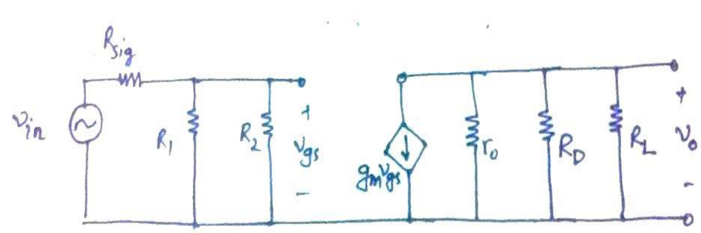
So, it is verified that transistor parameters are consistent with saturation current.
(b) Here,

$$g_m = \frac{2I_D}{V_{GS} - V_t} = \frac{2 \times 1\text{ mA}}{2 - 1\text{ V}} = 2\text{ mS}$$

$$r_o = \frac{V_A + V_{DS}}{I_D} = \frac{100 + 4\text{ V}}{1\text{ mA}} = 104\text{ k}\Omega$$

(c) Small-signal model:





(d) Here,

$$R_{in} = (10\ \text{M}\Omega \parallel 5\ \text{M}\Omega) = 3.33\ \text{M}\Omega$$

$$v_{gs} = \frac{3.33\ \text{M}\Omega}{3.33\ \text{M}\Omega + 0.1\ \text{M}\Omega} v_{sig} = 0.971$$

$$\frac{v_{gs}}{v_{sig}} = 0.971\ \text{V/V}$$

$$v_o = -g_m v_{gs}(r_o \parallel R_D \parallel R_L)$$

$$\Rightarrow \frac{v_o}{v_{gs}} = -g_m(r_o \parallel R_D \parallel R_L) = -(2\ \text{mS})(104\ \text{k}\Omega \parallel 7.5\ \text{k}\Omega \parallel 10\ \text{k}\Omega) = -(2\ \text{mS})(4.115\ \text{k}\Omega)$$

$$\frac{v_o}{v_{gs}} = -8.2\ \text{V/V}$$

$$\frac{v_o}{v_{sig}} = \frac{v_o}{v_{gs}} \times \frac{v_{gs}}{v_{sig}} = 0.971 \times (-8.2)$$

$$\frac{v_o}{v_{sig}} = -7.96\ \text{V/V}$$