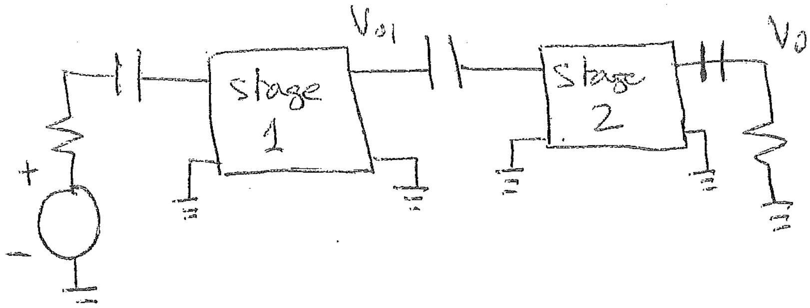
New topic/new lecture.

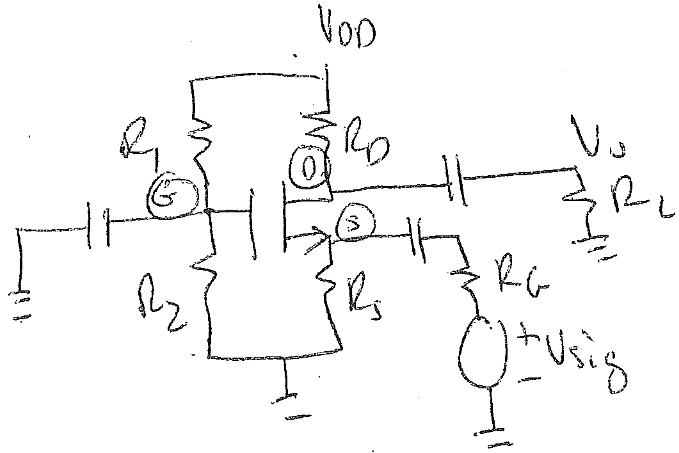
RC coupled multistage amplifiers:



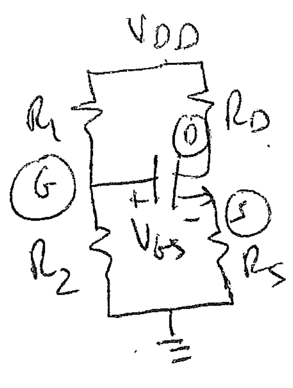
→ 1st identify each stage: CS, CD, CG

→ Decide how to analyze depending on stages.

→ Common-gate amplifier (not discussed before).



DC Analysis (similar to CS amplifier).



$$V_G = \frac{R_2}{R_1+R_2} V_{DD}$$

$$V_{GS} = V_G - R_S\left[\frac{k}{2}(V_{GS}-V_T)^2\right]$$

→ Find V_{GS}

→ Find I_D

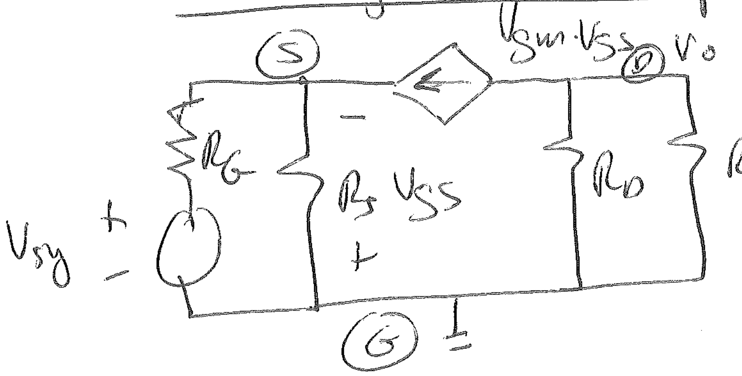
→ Determine saturation

$V_{GD} < V_T$

→ Find $g_m = k(V_{GS}-V_T)$

12/2/2016
Madhu's

Small signal of CG aplifier



Caps → shorts
V_{DD} → ground

$$\frac{V_o}{V_{gs}} = -g_m \cdot R_{eq}$$

Node at S to find $\frac{V_{gs}}{V_{sig}}$

$$\frac{V_s - V_{sig}}{R_G} + \frac{V_s}{R_s} = g_m \cdot V_{gs} \longrightarrow \text{and } V_{gs} = -V_s$$

$$\frac{V_s - V_{sig}}{R_G} + \frac{V_s}{R_s} = -g_m V_s$$

$$\frac{V_s}{R_G} + \frac{V_s}{R_s} + g_m V_s = \frac{V_{sig}}{R_G}$$

$$V_s\left(\frac{1}{R_G} + \frac{1}{R_s} + g_m\right) = \frac{V_{sig}}{R_G}$$

$$V_s\left(\frac{g_m \cdot R_s R_G + R_s + R_G}{R_s R_G}\right) = \frac{V_{sig}}{R_G}$$

$$\therefore \frac{V_s}{V_{sig}} = \frac{R_s}{g_m R_s R_G + R_s + R_G}$$

and $$\frac{V_{gs}}{V_{sig}} = \frac{-R_s}{g_m R_s R_G + R_s + R_G} \left(\frac{1/R_s}{1/R_s}\right)$$

or $$\frac{V_{gs}}{V_{sig}} = \frac{-1}{g_m R_G + 1 + \frac{R_G}{R_s}}$$ and $g_m R_G + 1 = R_G\left(g_m + \frac{1}{R_G}\right)$ → $\frac{1}{1/g_m \| R_G}$

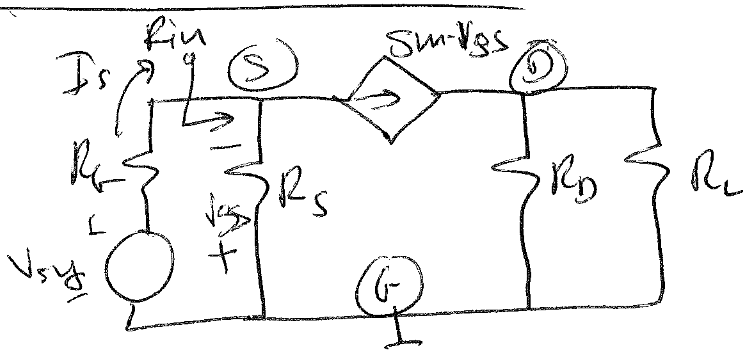
→ cont'd

↳ cont's

Finally: $$\frac{V_{gs}}{V_{sig}} = \frac{-1}{\frac{R_G}{R_S} + \frac{R_G}{\frac{1}{g_m}\|R_G}}$$

And $$\frac{V_o}{V_{sig}} = (-g_m R_{eq})\left(\frac{-1}{\frac{R_G}{R_S} + \frac{R_G}{\frac{1}{g_m}\|R_G}}\right)$$

Or using Input resistance:



$$R_{in} = \frac{V_s}{I_s}$$

Node (S):

$$\frac{V_s}{R_S} + \underbrace{\frac{V_s - V_{sig}}{R_G}}_{-I_s} = g_m V_{gs} \quad \text{and } V_{gs} = -V_s$$

$$\frac{V_s}{R_S} - I_s = -g_m \cdot V_s$$

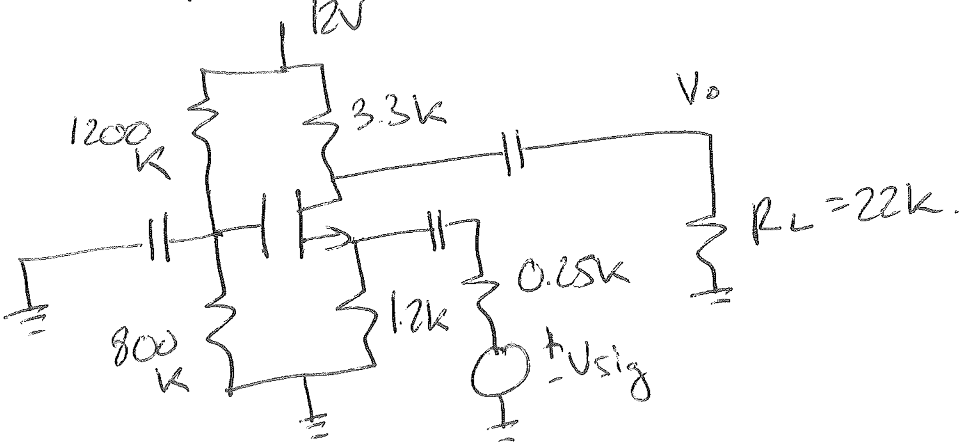
$$V_s\left(\frac{1}{R_S} + g_m\right) = I_s$$

$$R_{in} = \frac{V_s}{I_s} = \frac{1}{\underbrace{\frac{1}{R_S} + g_m}_{\text{sum of 2 conductances}}} = \frac{1}{g_m}\|R_S$$

And $$\frac{V_{gs}}{V_{sig}} = -\frac{R_{in}}{R_{in} + R_G}$$

② 12/2/2016
Madhu's

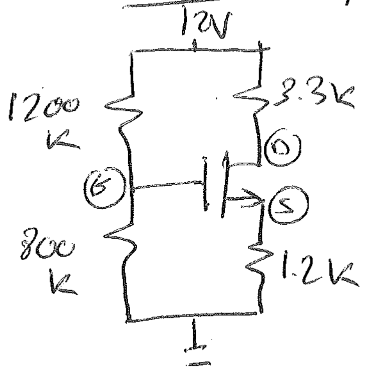
CG - amplifier example:



$K = 1.5 mA/V^2$

$V_T = 0.9V$

DC analysis



Caps → open.

$$V_G = 12 \cdot \frac{800}{800+1200} = 4.8 \text{ Volts}$$

$$4.8 - 1.2k\left(\frac{1}{2}(1.5mA/V^2)(V_{GS}-0.9)^2\right) = V_{GS}$$

$$4.8 - 0.9V_{GS}^2 + 1.62V_{GS} - 0.729 = V_{GS}$$

$$V_{GS} = 2.499V$$

$4.071 + 0.62V_{GS} - 0.9V_{GS}^2 = 0$

$V_{GS} = 2.499 V$

$= -1.81 V$

$V_S = (1.918mA)(1.2k) = 2.3V$ $\quad I_D = 1.918mA$

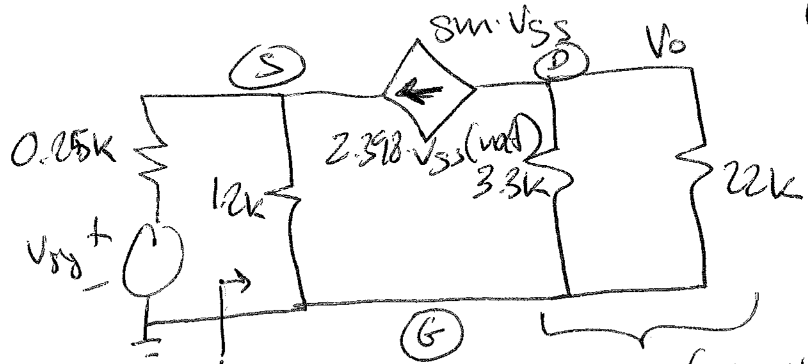
$$V_D = 12V - (1.918mA)(3.3k) = 5.672V$$

Check sat: $V_{DS} > V_{GS} - V_T$ $\quad \rightarrow \underbrace{V_{DS} = 3.37V}_{V_{DS} = 5.672 - 2.3V} > 2.499 - 0.9$ ✓

$$gm = 1.5(2.499 - 0.9) = 2.398mS$$

Small-signal eq. circuit

Caps → shorts
Sources → ground.



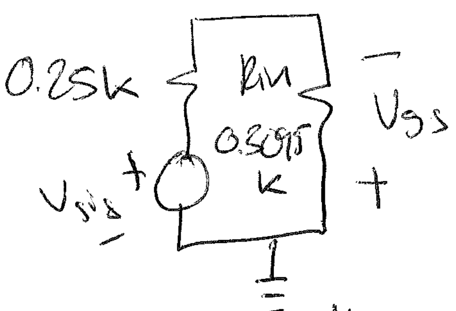
$R_{eq} = (3.3k \,||\, 22k) = 2.87k$

$R_{in} = 1.2 \,||\, \frac{1}{2.398}$

$R_{in} = 0.3095K = \frac{(1.2k)(0.417k)}{1.617k}$

$\frac{V_{gs}}{V_{sig}} = -\frac{R_{in}}{R_{in} + R_{sig}}$

$\frac{V_{gs}}{V_{sig}} = -\frac{0.3095}{0.25 + 0.3095} = -0.5531$



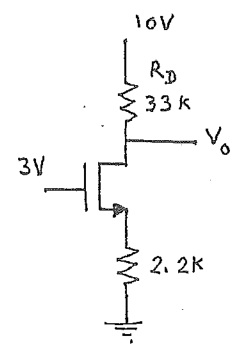
$\frac{V_o}{V_{gs}} = -g_m \cdot R_{eq}$

$\frac{V_o}{V_{gs}} = -2.398 \times 2.87 = -6.882$

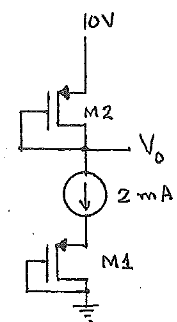
$\therefore \frac{V_o}{V_{sig}} = 3.806 \left(V/V\right) = (-0.5531)(-6.882)$

EE 381 ELECTRONICS I (Madhu)
REVIEW PROBLEMS FOR THE FINAL EXAM

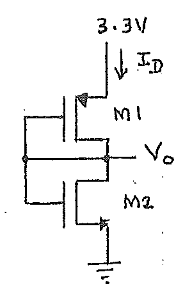
Problem 1: $k = 0.2$ mA/V^2 and $V_T = 1.5$ V.
(a) Find V_o.
(b) Find the maximum value that R_D can have before the transistor goes out of saturation. Find V_o for this condition.



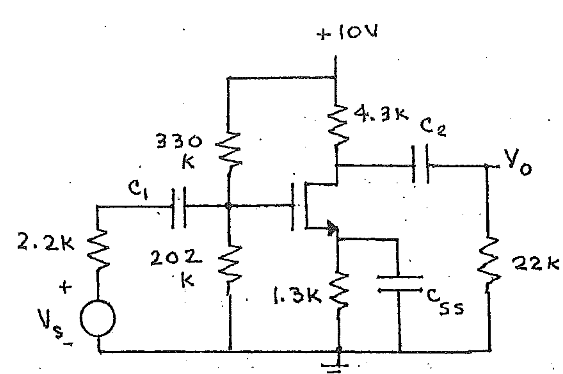
Problem 2: $k_1 = 1.25$ mA/V^2, $k_2 = 2.5$ mA/V^2. $|V_T| = 0.8$ V for both.
(a) Find V_o.
(b) Replace the current source by a resistor R_1. What is the value of R_1?



Problem 3: $\mu_n C_{ox} = 0.050$ mA/V^2 and $\mu_p C_{ox} = 0.025$ mA/V^2.
$|V_T| = 0.9$ V for both.
(a) If $(W/L) = 10$ for both transistors, find I_D and V_o.
(b) Repeat the calculations of Part (a) if (W/L) of the NMOS is changed to 4, keeping (W/L) of the PMOS at 10.

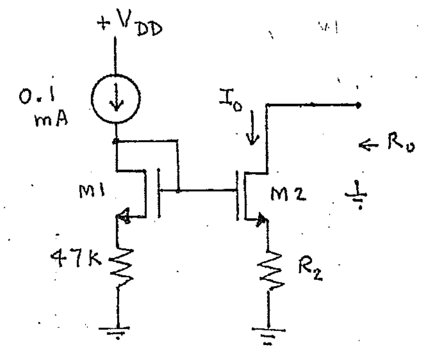


Problem 4: $k = 0.9$ mA/V^2 and $V_T = 0.5$ V. $C_{gs} = 12$ pF. $C_{gd} = 4$ pF. $C_{ds} = 6$ pF. Determine the midband gain and the upper cutoff frequency.



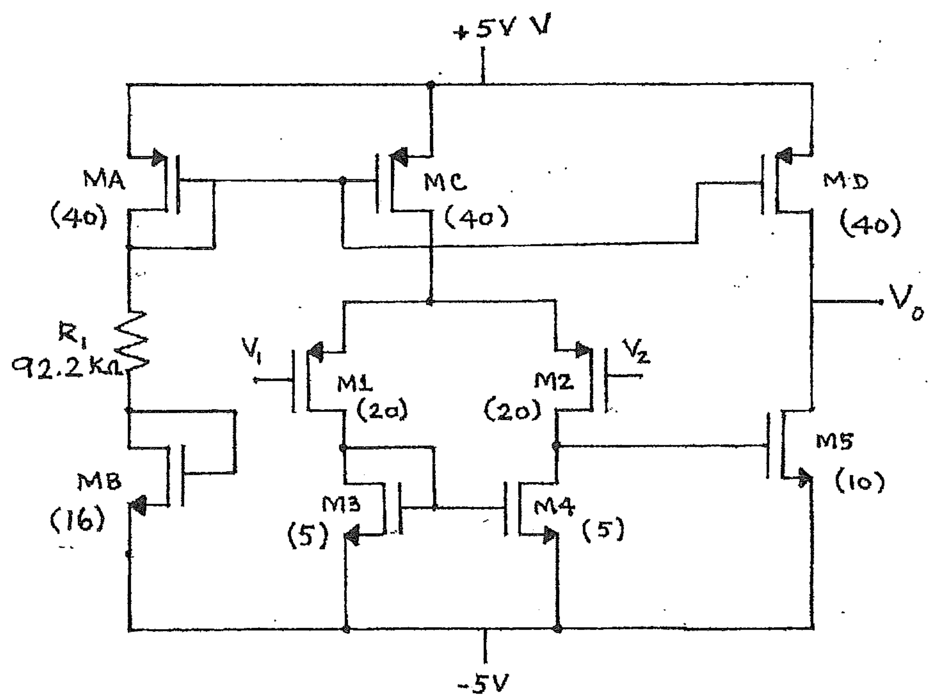
Problem 5: The amplifier of the previous problem is required to have a lower cutoff frequency of 30 Hz. (Note the units!) Select the value of C_{SS} so that it results in a pole at the specified lower cutoff frequency. Select the value of C_I so that the pole due to it cancels the zero caused by C_{SS} and select the value of C2 so that the pole due to it is at 3 Hz.

Problem 6: $\mu_n C_{ox} = 0.092$ mA/V^2. $|V_T| = 0.9$ V. $(W/L) = 62.5$. $\lambda = 0.025$ V^{-1} for both.
(a) Find the value of R_2 so as to make $I_o = 0.05$ mA.
(b) Find the output resistance R_o.



Problem 7: In the 2-stage CMOS op amp shown below, the sizing ratios of the different transistors are shown in parenthesis. $\mu_n C_{ox} = 0.160$ mA/V^2 and $\mu_p C_{ox} = 0.064$ mA/V^2.

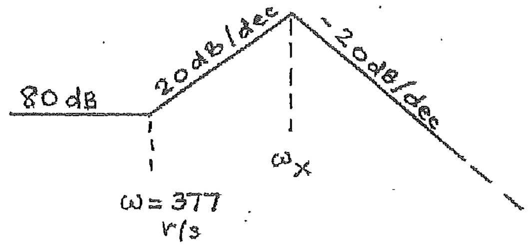
$|V_T| = 0.7$ V for all transistors. $\lambda = 0.025$ V^{-1} for NMOS and 0.05 V^{-1} for the PMOS devices.



(a) Determine the Q point values of the drain and gate voltages. Assume that $V_o = 0$ at the Q point.

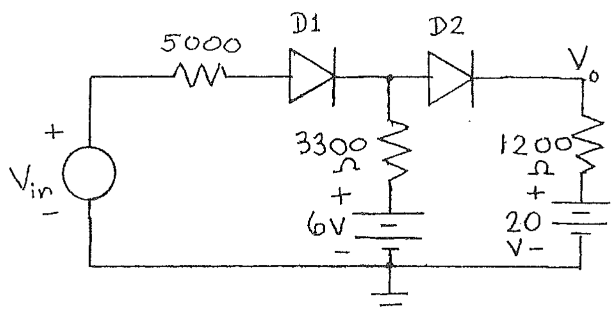
(b) Determine the diff mode gain.

Problem 8: The asymptotic value of the gain at ω_x is given as 97 dB.onstz
(a) Write the expression of the gain function. Be sure to evaluate the constant K.
(b) Draw the phase plot. Be sure to include all relevant numerical information in the diagram.



Problem 9: A two stage op amp has an equivalent circuit with parameters and element values as follows: $g_{m2} = 1.5$ mS; $R_{o1} = 40$ kΩ; $C_1 = 13.5$ pF; $g_{m5} = 0.8$ mS; $R_{o2} = 62.5$ kΩ; $C_2 = 1.2$ pF.
(a) Sketch the Bode magnitude and phase plots.
(b) Determine the value of the Miller compensation capacitor C_C needed to introduce a phase margin of 60°.

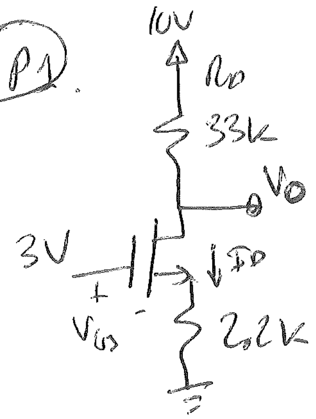
PROBLEM 10: Assume ideal diodes. Find the range of values of V_{in} for each of the following two states:
(a) both diodes are ON.
(b) D1 ON and D2 OFF.



REVIEW PROBLEMS FOR FINAL EXAM

12/5/2016

Madhu

(P1). 

$k = 0.2\,mA/V^2$

$V_T = 1.5V$

a) Find V_O.

b) Find max value of R_D for saturation and V_O for this condition.

(a) $3 - 2.2\left(\frac{1}{2}\,0.2\,(V_{GS} - \overset{1.5V}{V_T})^2\right) = V_{GS}$

$3 - 0.22\,V_{GS}^2 + 0.66\,V_{GS} - 0.495 = V_{GS}$

$2.505 - 0.34\,V_{GS} - 0.22\,V_{GS}^2 = 0$

$V_{GS} = -4.23V$

$= 2.689V$

$\rightarrow V_{GS} = 2.689V$

$I_D = 0.1414\,mA.$

And $V_O = 5.335V = 10 - I_D R_D$

(b) $V_{GD} = V_T \leq 1.5V$

$V_{GD\,max} = 1.5V$

$V_D = 1.5V$ (min)

$R_D = 60.11k.$

$V_{DS} = V_{GS} - V_T = \overset{2.689}{3} - 1.5 = \cancel{1.5V}\ 1.189V$

$V_{DS} = \underbrace{10 - I_D \cdot R_D}_{V_D} - \underbrace{I_D \cdot R_S}_{V_S}$

~~$V_{DS} = 1.189 = [10 - (0.1414 \cdot R_D)] - 0.31108$~~

~~$R_D = \frac{1.189 + 0.311}{0.1414} = 3.33k$~~

$V_{DS} = 1.189 = \underbrace{(10 - I_D R_D)}_{V_D} - \underbrace{I_D R_S}_{V_S}$

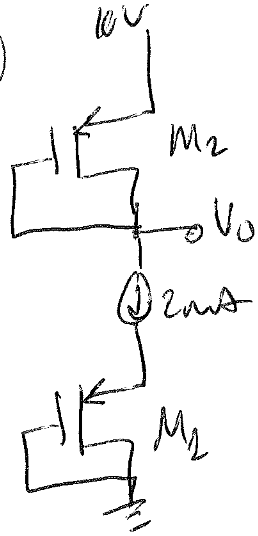
$1.189 = 10 - 0.1414 \cdot R_D - 0.311$

$1.189 - 10 + 0.311 = -0.1414\,R_D$

$R_D = \frac{8.5}{0.1414} = 60.11k.$

$\boxed{V_O = 10 - 8.5 = 1.5V}$

(#2)



$k_1 = 1.25\,mA/V^2$ $\quad |V_T| = 0.8V$

$k_2 = 2.5\,mA/V^2$

(a) V_o.

M_2: $I_D = 2mA$

$2 = \left(\frac{1}{2}\right) 2.5mA\,(V_{GS_2} - 0.8)^2$

$V_{OV} = \sqrt{\frac{4}{2.5}} = 1.26V$

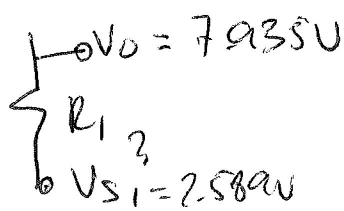
$V_{GS} = V_{OV} + V_T$

$V_{GS_2} = 2.065V$

$V_o = 7.935V$

$= (10 - 2.065V)$

(b) Replace current source by R_1. What is R_1?



$2mA = \frac{1}{2}\left(1.25\,mA/V^2\right)\left(V_{OV}^2\right)$

$\cancel{V_{GS_1}} = \therefore V_{SG_1} = 2.589V$

$V_{S_1} = 2.589V$

$R = \frac{7.935 - 2.589}{2mA} = 2.673k$

P3

② 12/5/2016
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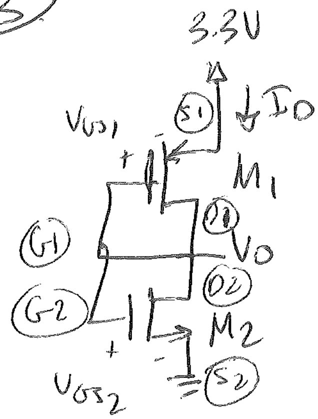


$\mu_n C_{ox} = 0.05\ mA/V^2$

$\mu_p C_{ox} = 0.025\ mA/V^2$

$|V_T| = 0.9V$

(a) $\frac{W}{L} = 10$ for both. Find I_D + V_O

$k_n = 10 \cdot 0.05\,mA/V^2 = 0.5\,mA/V^2$

$k_p = 10 \cdot 0.025\,mA/V^2 = 0.25\,mA/V^2$

$I_{Dn} = I_{Dp}$

$$\frac{1}{2} 0.5\,mA/V^2 (V_{GS_n} - V_T)^2 = \frac{1}{2} 0.25\,mA/V^2 (V_{SG_p} - V_T)^2$$

$$\frac{V_{SG_1} - 0.9}{V_{GS_2} - 0.9} = \underbrace{\sqrt{\frac{0.25}{0.125}}}_{1.414}$$

$V_{SG_1} - 0.9 = 1.414 V_{SG_2} - 1.273$

2 eq, 2 unknowns $\begin{cases} V_{SG1} = 1.414 V_{GS2} - 0.3728 \\ V_{SG1} + V_{GS2} = 3.3 \end{cases}$

$V_{SG1} = 1.778V$

$V_{GS2} = 1.521V$

(b) $\left(\frac{W}{L}\right)_n = 4$ $\left(\frac{W}{L}\right)_p = 10$

$k_n = 0.2\,mA/V^2$

$k_p = 0.25\,mA/V^2$

$0.1 (V_{GS2} - 0.9)^2 = 0.125 (V_{SG1} - 0.9)^2$

$$\frac{V_{GS2} - 0.9}{V_{SG1} - 0.9} = \sqrt{\frac{0.125}{0.1}}$$

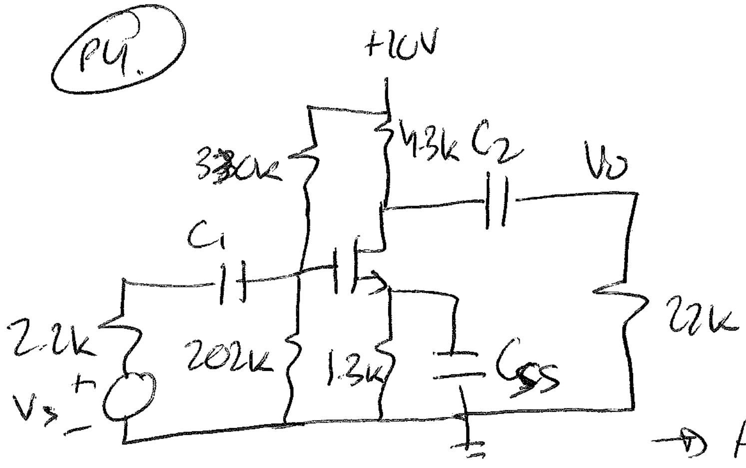
$V_{GS2} - 0.9 = 1.118 V_{SG1} - 1.006$

$1.118 V_{SG1} - V_{GS2} = 0.1062$
$V_{SG1} + V_{GS2} = 3.3$
2 eq, 2 unknowns

$V_{SG1} = 1.608V$

$V_{GS2} = \cancel{1.392V}$ 1.692V

P4.



$k = 0.9\ mA/V^2$

$V_T = 0.5$

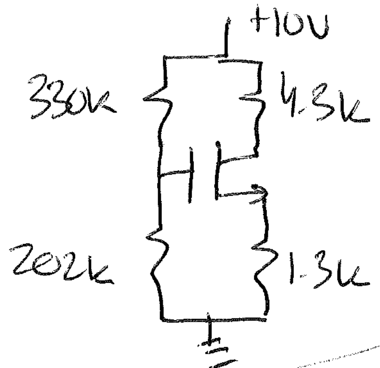
$C_{gs} = 12pF$

$C_{gd} = 4pF$

$C_{ds} = 16pF.$

→ Find midband gain and upper cutoff frequency.

D.C. Analysis



Caps → open

$$V_G = 10V \cdot \frac{202k}{202k + 330k} = 3.797V$$

$$V_{GS} = 3.797 - \left(\frac{1}{2}\, 0.9 (V_{GS} - 0.5)^2\right)(1.3k)$$

$$V_{GS} = 3.797 - 0.585 (V_{GS} - 0.5)^2$$

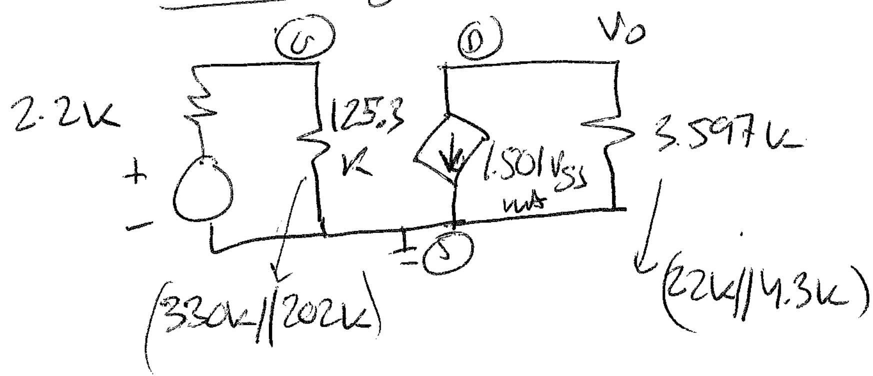
$$3.797 - 0.585 V_{GS}^2 + 0.585 V_{GS} - 0.14625 = V_{GS}$$

$V_{GS} = 2.168V$

$g_m = 1.501 mS$

$g_m = k (V_{GS} - V_T)$

Small signal midband:



$$\frac{V_o}{V_{gs}} = -5.399$$

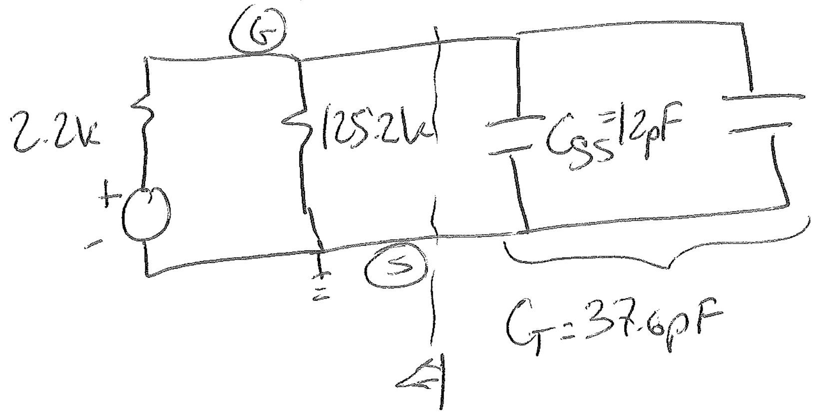
$$\frac{V_{gs}}{V_{sig}} = \frac{125.3}{125.3 + 2.2} = 0.9827$$

$A_{mid} = -5.306$

③ 12/5/2016
Madlu

→ Upper cut-off frequency

ω_{hi} Input side:

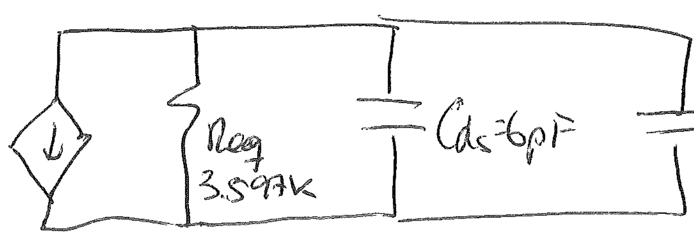


$C_M = C_{gd}(1+g_m \cdot R_{eq})$
$= 4pF(1+1.501mS \cdot 3.597k)$
$C_M = 4(1+5.399) = 25.6pF$

$R_{TH} = 125.2k // 2.2k = 2.162k.$

$$\therefore \quad \omega_{hi(in)} = \frac{1}{(2.162k)(37.6pF)} = 1.230\times10^7 \text{ r/s}$$

ω_{hi} output side.



$C'_M = C_{gd}\left(1+\frac{1}{g_m R_{eq}}\right)$
$C'_M = 4pF\left(1+\frac{1}{5.399}\right) = 4.741 pF$

$$\omega_{hi(out)} = \frac{1}{(3.597\times10^3)(10.741\times10^{-12})} = 2.588\times10^7 \text{ r/s}$$

No dominant pole

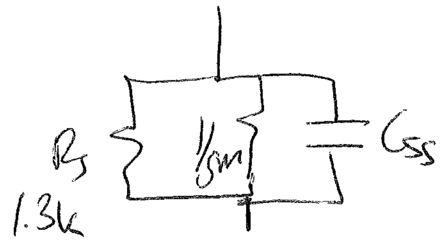
$$\left|\frac{(1.23\times10^7)(2.588\times10^7)}{(j\omega+1.23\times10^7)(j\omega+2.588\times10^7)}\right| = 0.707$$

← to find 3dB pole.

$$\therefore \boxed{\omega_{hi} = 1.044\times10^7 \text{ r/s}}$$

(P5) $\rightarrow f_{Lo} = 30\,Hz \rightarrow \omega_{Lo} = 188.5\ r/s$

Bypass capacitor $C_{SS} \rightarrow \omega_p = 188.5\ r/s$



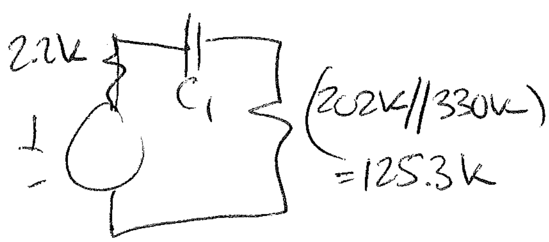
$$\omega_p = 188.5\ r/s = \frac{1}{(1.3k // 0.662k)\cdot C_{SS}}$$

$$\frac{1}{1.801\,ms} = 0.662k$$

$$C_{SS} = \frac{1}{(188.5\ r/s)(0.4405\times10^3)} = 12.04\,\mu F$$

$$\omega_z \text{ due to } C_{SS} = \frac{1}{R_S\cdot C_{SS}} = \frac{1}{(1.3\times10^3\,\Omega)(12.04\times10^{-6}F)} = 63.89\ r/s$$

$\rightarrow$ Want C_1 to cancel that zero (ω_z of C_{SS})

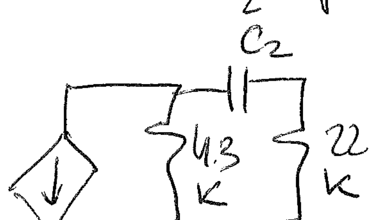


$$\omega_{pC_1} = \frac{1}{C_1\cdot(127.5\times10^3\,\Omega)} = 63.89\ r/s$$

$$\therefore C_1 = \frac{1}{(63.89\ r/s)(127.5\times10^3\,\Omega)}$$

$$C_1 = 122.8\,nF$$

$\rightarrow$ Make C_2's pole at $0.1\times f_{low} = 3\,Hz$ $\quad \omega_{pC_2} = 6\pi\ r/s$



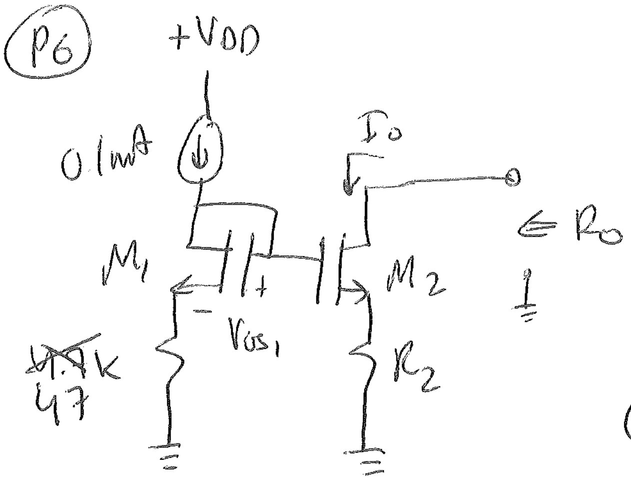
$$\omega_{pC_2} = \frac{1}{C_2\cdot(26.3k)} = 6\pi\ r/s$$

$$C_2 = \frac{1}{(26.3k)(6\pi\ r/s)} = 2.017\,\mu F$$

12/7/2016

Madhu

(P6)



$\mu_n C_{ox} = 0.092\,mA/V^2$

$|V_T| = 0.9V$

$\frac{W}{L} = 62.5$, $\lambda = 0.025V^{-1}$ (for both)

(a) Find R_2 to make $I_O = 0.05mA$

(b) Find output resistance R_o.

(a) $I_{D1} = 1mA = \frac{1}{2}(0.092mA/V^2)(62.5)\cdot\underbrace{(V_{GS1} - \overset{0.9V}{V_T})}_{V_{OV}}^2$

$V_{OV_1} = 0.186$

$V_{GS1} = 1.086V$

$V_{G1} = (47k)(0.1mA) + 1.086V = 5.786V$

Also $V_{G2} = 5.786V$

For $I_{D2} = 0.05mA = \frac{1}{2}(0.092mA/V^2)(62.5)(V_{OV})^2$

$V_{OV_2} = \cancel{0.186}\ 0.032$

$V_{GS_2} = 1.032V$

$\therefore\ V_{GS_2} = V_{G_2} - V_{S_2}$

$1.032V = 5.786 - V_{S_2}$

$V_{S_2} = 4.754 = R_2\cdot(0.05)$

$R_2 = 95.08k\Omega$.

OR: $1.032 = 5.786 - R_2\cdot(0.05)$

$R_2 = 95.08k\Omega$

b) Find output resistance R_o:

Draw small signal circuit, need $g_{m1} = 0.092 \times 62.5 (V_{ov1})$

$1.086 - 0.9$
$= 0.186$

$g_{m1} = 1.07 \text{ mS}$

$1.032 - 0.9$
$= 0.132$

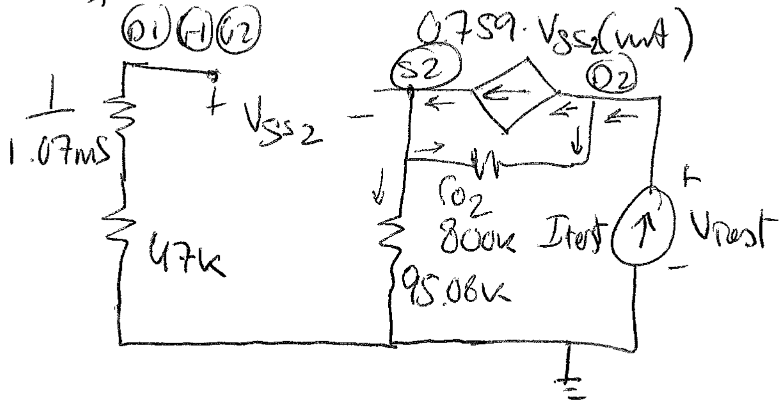
and $g_{m2} = 0.092 \times 62.5 (V_{ov2})$

$g_{m2} = 0.759 \text{ mS}$

and $r_{o2} = \dfrac{1}{\lambda \cdot I_{D2}} = \dfrac{1}{0.025 \times 0.05}$

$r_{o2} = 800k\Omega$

eq. circuit.



$V_{gs2} = -V_{s2}$ since $V_{g2} = 0V$ (no current flowing)

Node S_2: $\dfrac{V_{s2}}{95.08k} + \dfrac{V_{s2} - V_{test}}{800k} = 0.759(-V_{s2})$

$0.77076 V_{s2} - 1.25 \times 10^{-3} V_{test} = 0 \longrightarrow (1)$

Node D_2: $\dfrac{V_{test} - V_{s2}}{800} = I_{test} - 0.759(-V_{s2})$

$-0.76025 V_{s2} + 1.25 \times 10^{-3} V_{test} = I_T$

set $I_T = 1mA$

$-0.76025 V_{s2} + 1.25 \times 10^{-3} V_{test} = 1mA \rightarrow (2)$

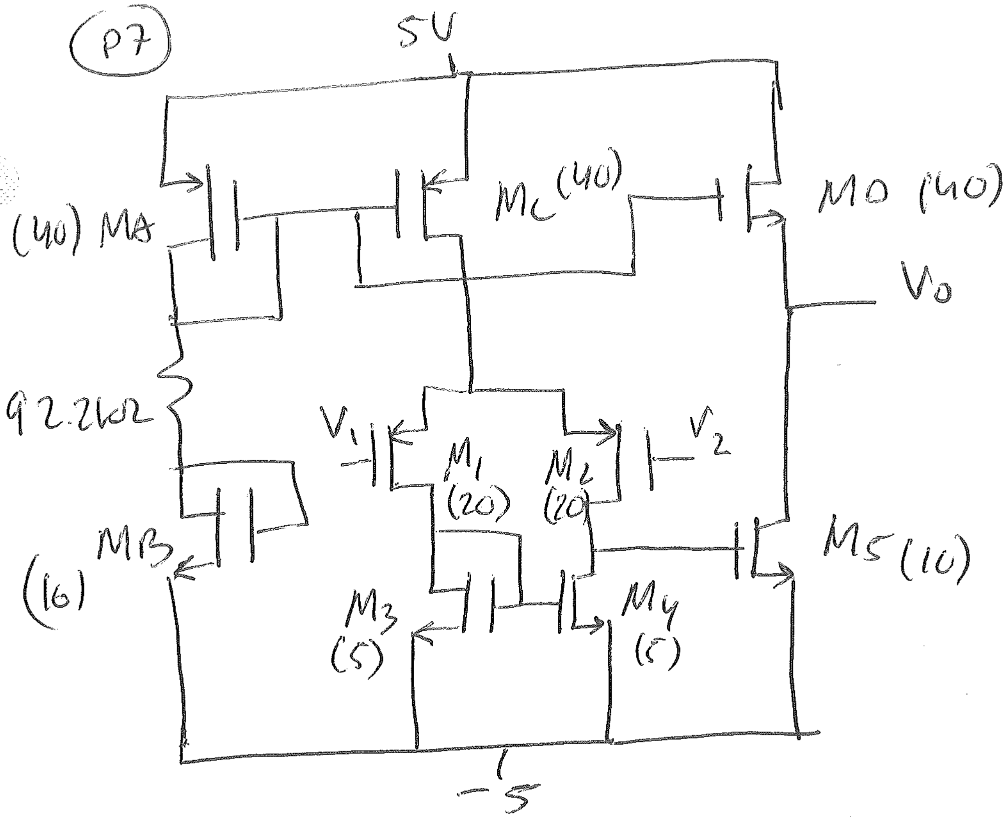
$V_{s2} = 95.15V$

$V_{test} = 5.867 \times 10^4$

$\therefore R_o = \dfrac{5.867 \times 10^4}{1 \times 10^{-3}} = 58.67 M\Omega$

12/7/2016 (2)

(P7)



$K_A = 0.064 \times 40 = 2.56 mA/V^2$

$K_B = 0.16 \times 16 = 2.56 mA/V^2$

$\therefore V_{SGA} = V_{GSB}$

$5 - V_{SGA} - 92.2k\left(\frac{1}{2}\right)(2.56)\left(V_{SGA} - 0.7\right)^2 - V_{SGA} = -5$