A	81 - 100
B	61 - 80
C	41 - 60

μ 66.7

σ 19.6

MED 65

Name SOLUTIONS

ECE Box # ____________

Problem	Score	Points
1	21.1	30
2	19.6	30
3	13.5	20
4	12.5	20

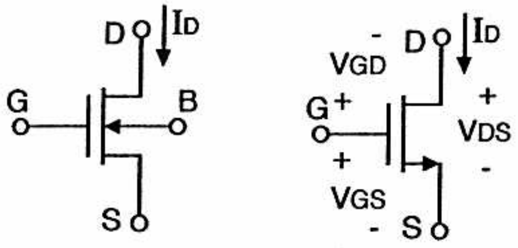
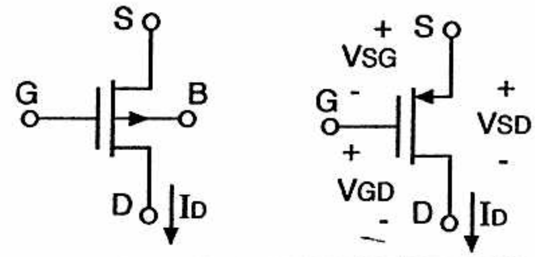
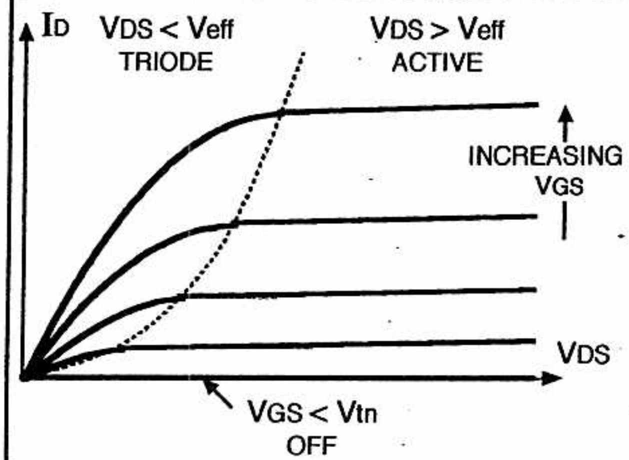
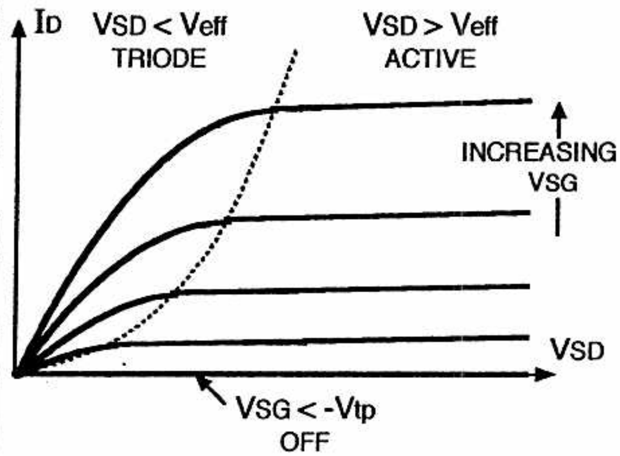
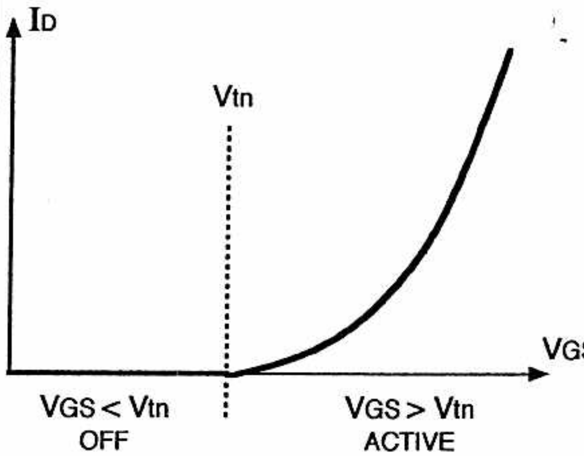
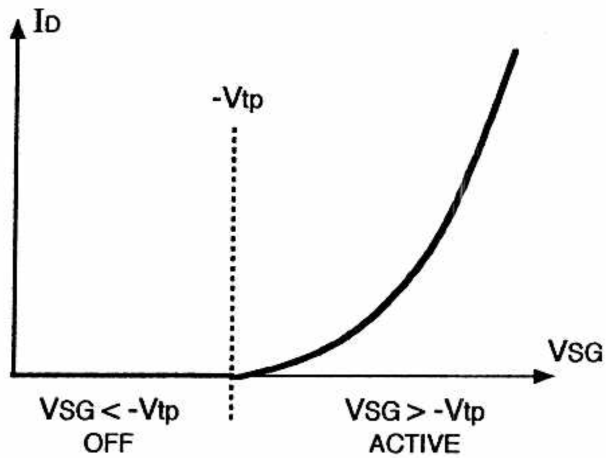
EE4902 C2002

Analog IC Design

Exam 2

- This is a **closed book test!**
- Show **all** your work. Partial credit may be given. If you think you need something that you can't remember, write down what you need and what you'd do if you remembered it.
- **Look for the simple, straightforward way to solve the problem for the level of accuracy required. Don't get entangled in unnecessary algebra.**
- You may assume all op-amps to be ideal, except as otherwise noted.
- As in real life, some problems may give you more information than you need. Don't assume that all information must be used! It's your job to decide what's relevant to the solution.
- You have until 12 noon to complete this exam. There are four problems on a total of 13 pages.

MOSFET LARGE SIGNAL CHARACTERISTICS

	N CHANNEL	**P CHANNEL**
CIRCUIT SYMBOL		
ACTIVE	$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \underbrace{(V_{GS} - V_{tn})}_{V_{eff}}{}^2 [1 + \lambda_n (V_{DS} - V_{eff})]$	$I_D = \frac{\mu_p C_{ox}}{2} \frac{W}{L} \underbrace{(V_{SG} + V_{tp})}_{V_{eff}}{}^2 [1 + \lambda_p (V_{SD} - V_{eff})]$
I_D-V_{DS} CHARACTERISTIC		
I_D-V_{GS} CHARACTERISTIC **(ACTIVE REGION)**		
TRIODE REGION	$I_D = \mu_n C_{ox} \frac{W}{L} [(V_{GS} - V_{tn}) V_{DS} - \frac{V_{DS}^2}{2}]$	$I_D = \mu_p C_{ox} \frac{W}{L} [(V_{SG} + V_{tp}) V_{SD} - \frac{V_{SD}^2}{2}]$

1. This problem involves design of a common source amplifier circuit with active load. The circuit is shown in Figure 1a.

You may assume that the substrate (body) terminal is tied to the source terminal.

Use the following MOSFET parameters for this $2\mu m$ process:

Parameter	N-channel	P-channel	Units
V_t	+1.10	-1.20	V
μC_{ox}	5.2E-5	1.5E-5	A/V^2
λ	0.03	0.02	V^{-1}

a) Choose R_B for a current of I_B=200μA in the current mirror. [4]

R_B = 14.9 kΩ

b) Choose the input bias voltage V_{BIAS} to achieve an output voltage in the linear range (both M1 and M2 in the active region). [4]

V_{BIAS} = 2.081 V

c) Determine the magnitude of the low-frequency small-signal gain from v_{in} to v_{out}. [8]

$$|a_v| = \left|\frac{v_{out}}{v_{in}}\right| = 40.8$$

d) Determine the maximum and minimum output voltages for which both M1 and M2 are in the active region. [4]

$V_{OUT(MAX)}$ = 4.18V } M2 TRIODE CRASH

$V_{OUT(MIN)}$ = 0.981V } M1 TRIODE CRASH

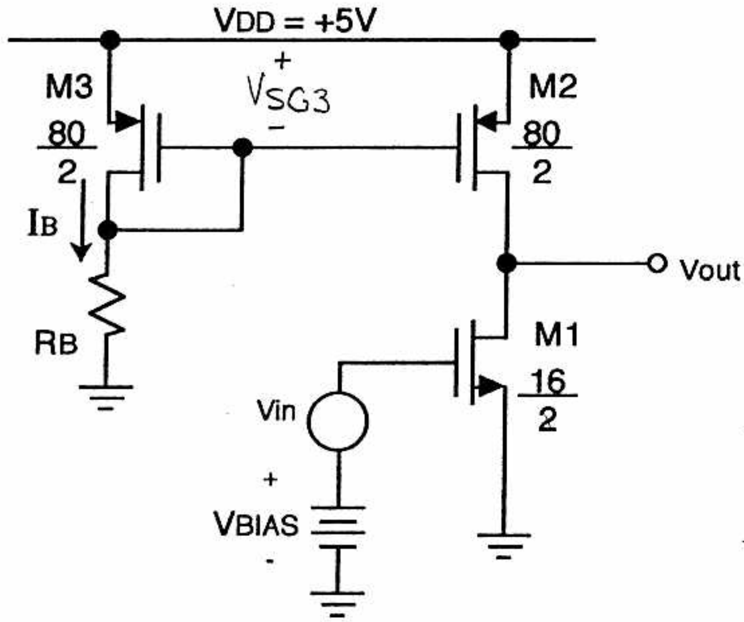


Figure 1a.

$$R_B = \frac{V_{DD} - V_{SG}}{I_B} \qquad V_{SG3}:\ 200\mu A = \frac{1.5E\text{-}5}{2}\,\frac{80}{2}\,\underbrace{(V_{SG3} + 1.2)}_{0.816\,V = V_{eff}}{}^2 \Rightarrow V_{SG} = 2.016\ V$$

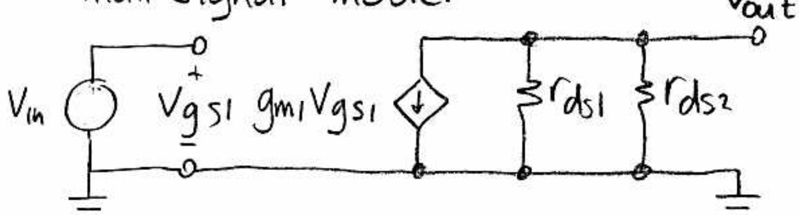
$$R_B = \frac{5V - 2.016}{200\mu A} = 14.9\ K\Omega$$

V_{BIAS} should make M1 I_D also be $200\mu A$

$$200\mu A = \frac{5.2E\text{-}5}{2}\,\frac{16}{2}\,\underbrace{(V_{BIAS} - 1.1V)}_{V_{eff} = 0.981V}{}^2 \Rightarrow V_{BIAS} = 2.081\ V$$

---

small signal model



$$g_{m1} = \frac{2(200\mu A)}{0.981V} = 408\mu A/V$$

$$r_{ds1} = \frac{1}{\lambda I_{D1}} = \frac{1}{(0.03)(200\mu A)} = 167K\Omega$$

$$r_{ds2} = \frac{1}{\lambda I_{D2}} = \frac{1}{(0.02)(200\mu A)} = 250K\Omega$$

***** MORE ON THE NEXT PAGE !!! *****

$$|a_v| = g_{m1}(r_{ds1} \| r_{ds2}) = 40.8$$

A load impedance of 150kΩ || 20pF is added to the output as shown in Figure 1b.

e) Will the low-frequency small signal gain magnitude $|a_v|$ decrease, remain the same, or increase?

[1]

DECREASE **SAME** **INCREASE**

EXPLAIN! [4]

R_L in parallel with r_{ds1}, r_{ds2}
reduces $r_{ds1} \| r_{ds2}$ term to $r_{ds1} \| r_{ds2} \| R_L$

f) Determine the DC gain and 3-dB bandwidth frequency ($f_{3\text{-dB}}$) for the circuit with the load impedance of 150kΩ || 20pF added to the output.

[5]

DC gain = 24.5

$f_{3\text{-dB}}$ = 132 kHz

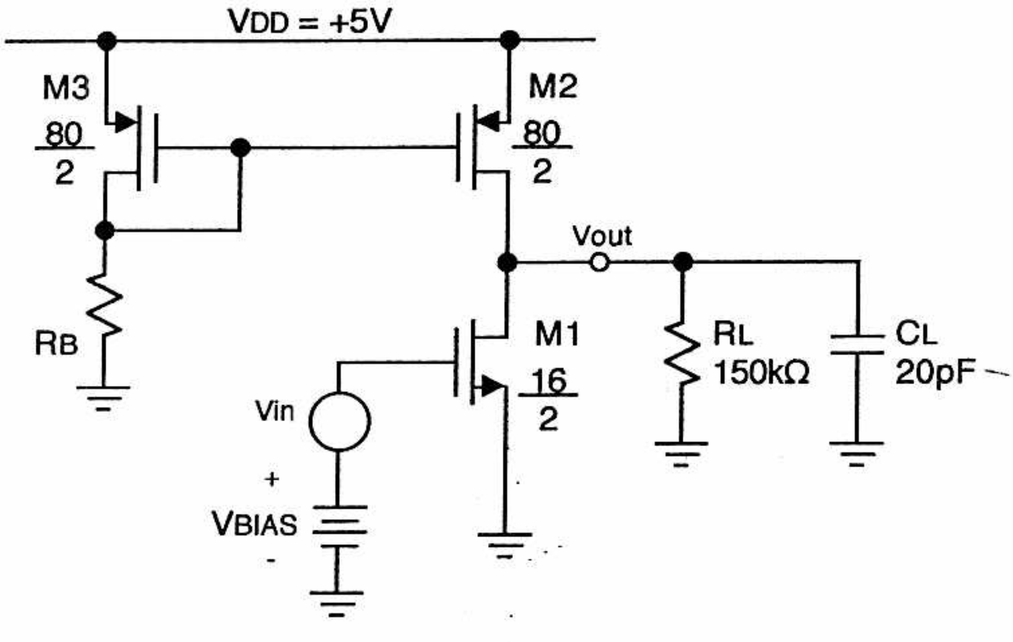
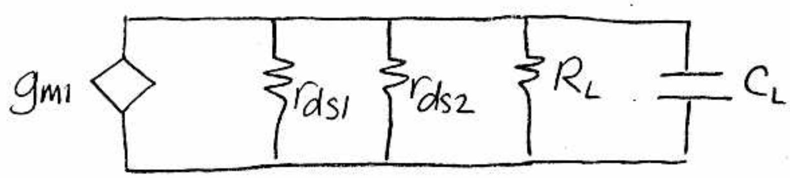


Figure 1b.

New small signal model



DC gain now

$$g_{m1}\underbrace{\left(r_{ds1} \| r_{ds2} \| R_L\right)}_{167K \| 250K \| 150K \, = \, 60 \ k\Omega} = 24.5$$

f_{3dB}

$$\frac{1}{2\pi\,(60\ k\Omega)\,20pf} = 132\ KHz$$

2. This problem concerns the design of the differential amplifier shown in Figure 2. You may assume that the substrate (body) terminal is tied to the source terminal. You may also ignore channel length modulation (assume $\lambda=0$)

Use the following MOSFET parameters for this $2\mu m$ process:

Parameter	N-channel	P-channel	Units
V_t	+1.10	-1.20	V
μC_{ox}	5.2E-5	1.5E-5	A/V^2

a) Choose I_{BIAS} for an output DC bias level of $V_{O1(DC)} = V_{O2(DC)} = +3.0V$. **[6]**

$I_{BIAS} =$ 800μA

400μA I_D in R_{D1}, R_{D2}

b) Determine the magnitude of the low-frequency small-signal **differential mode** gain $|a_{v(dm)}|$ from differential input $v_{in(dm)}=v_+-v_-$ to differential output $v_{out(dm)}=v_{o1}-v_{o2}$. Numerical result required! **[6]**

$$|a_{v(dm)}| = \left|\frac{v_{out(dm)}}{v_{in(dm)}}\right| = \left|\frac{v_{o1}-v_{o2}}{v_+ - v_-}\right| = 6.5$$

FROM HALF CIRCUIT

$g_{m1} R_D$ $\qquad g_m = \sqrt{2(400\mu A)\, 5.2E\text{-}5\, \frac{80}{2}} = 1.29\ mA/V$

$(1.29\ mA/V)\ 5K\Omega = 6.5$

c) Determine the magnitude of the low-frequency small-signal **common mode** gain $|a_{v(cm)}|$ from input $v_{cm}=v_+=v_-$ to output v_{o1}. Numerical result required! **[6]**

$|a_{v(cm)}| = 0$

I_{BIAS} ideal current source

If $V_+ = V_-$, $V_{GS1} = V_{GS2}$, $I_{D1} = I_{D2} = \frac{I_{BIAS}}{2} \Rightarrow V_{O1}, V_{O2}$ unchanged

d) Using the axes on the opposite page, sketch the total output voltages V_{O1} and V_{O2} when the input is a pure **differential** signal of 200mV sin 2π(1kHz)t. On your sketch, be sure to label bias voltages and signal amplitudes. **[6]**

e) Using the axes on the opposite page, sketch the total output voltages V_{O1} and V_{O2} when the input is a pure **common mode** signal of 1V sin 2π(1kHz)t. On your sketch, be sure to label bias voltages and signal amplitudes. **[6]**

$\frac{2V}{5K\Omega} = 400\mu A$

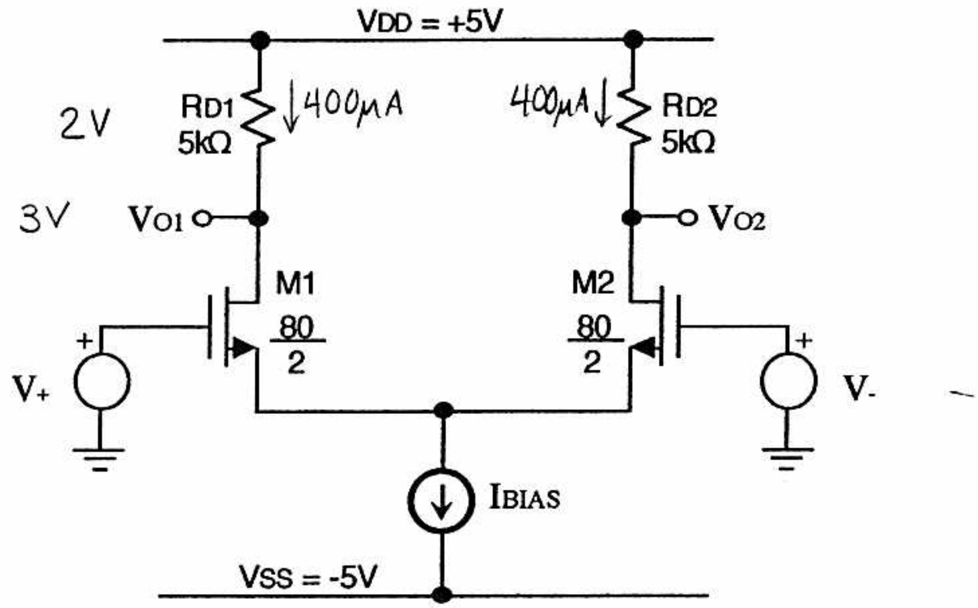
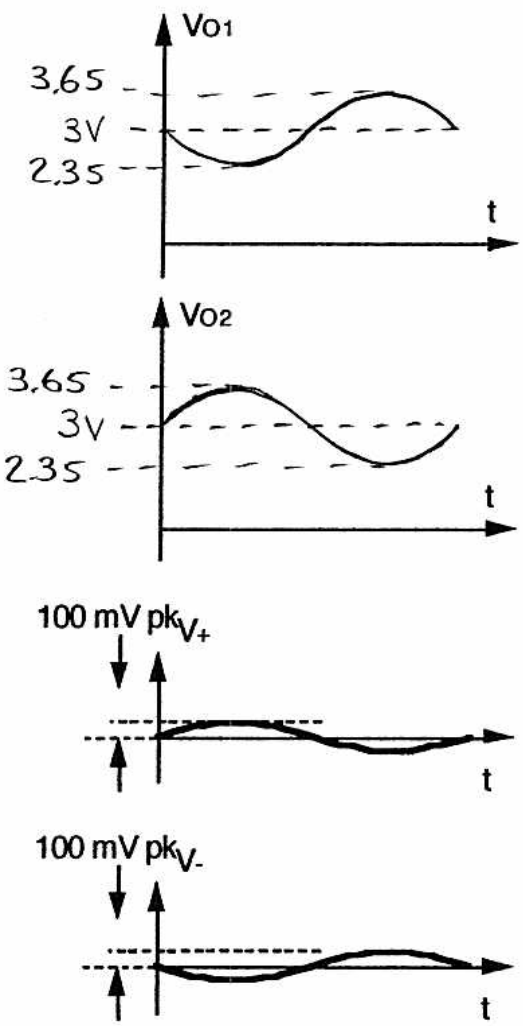
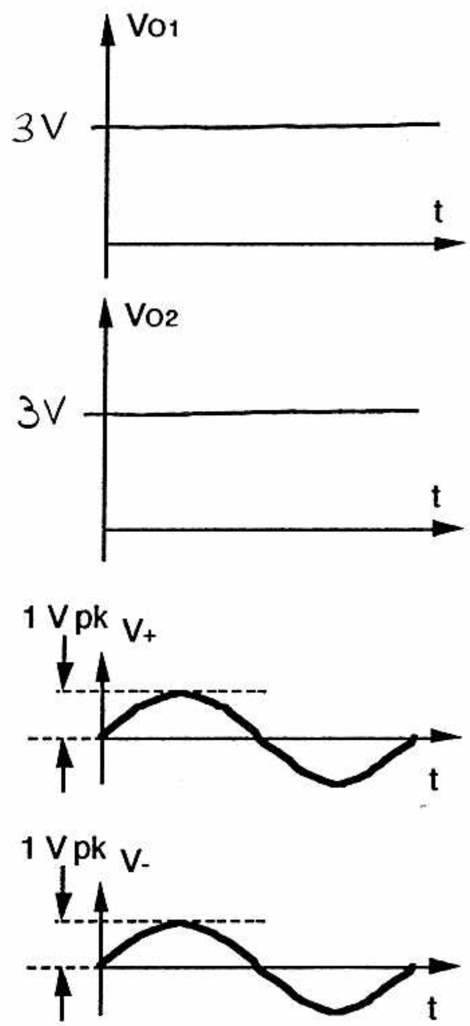


Figure 2.

Axes for part (d):



Axes for part (e):



3. Your design from the previous problem is modified by splitting the bias current source and inserting resistor R_S between the sources of M1 and M2, as shown in Figure 3.

a) Will the magnitude of the low frequency small-signal **common mode** gain $|a_{v(cm)}|$ decrease, remain the same, or increase? **[1]**

DECREASE **REMAIN THE SAME** **INCREASE**

EXPLAIN! **[6]**

NO CURRENT THROUGH R_S (OPEN CIRCUIT)

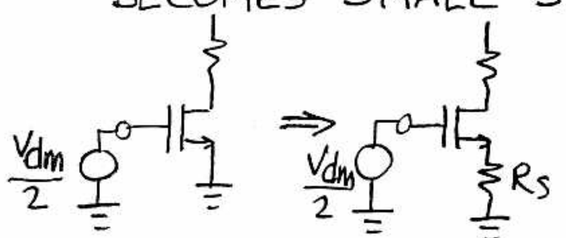
NO CHANGE

b) Will the magnitude of the low frequency small-signal **differential mode** gain $|a_{v(dm)}|$ decrease, remain the same, or increase? **[1]**

DECREASE **REMAIN THE SAME** **INCREASE**

EXPLAIN! **[6]**

CONNECTED POINT OF SYMMETRY BECOMES SMALL SIGNAL GROUND



LESS SIGNAL VOLTAGE ACROSS V_{gs}

c) Determine the magnitude of the low frequency small-signal differential mode gain $|a_{v(dm)}|$ for the circuit of Figure 3. **[6]**

$$|a_{vdm}| = \frac{g_{m1} R_{D1}}{1 + \frac{g_{m1} R_S}{2}}$$

$$g_{m1} = \sqrt{2(400\mu A)\frac{80}{2}(5.2E\text{-}5)} = 1.29 \text{ mA/V}$$

(SAME DC BIAS!)

$$|a_{vdm}| = \frac{(1.29\text{mA/V})(5\text{k}\Omega)}{1 + \frac{(1.29\text{mA/V})(5\text{k}\Omega)}{2}}$$

$= 1.53$ approximating $\frac{R_{D1}}{R_S/2} \approx 2$ OK!

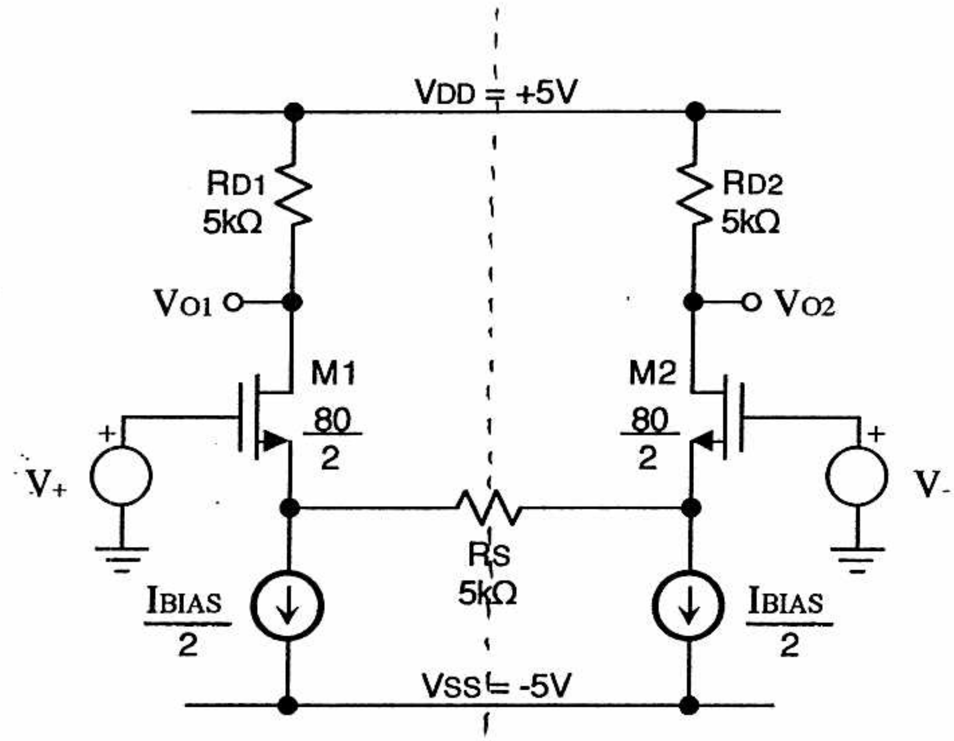
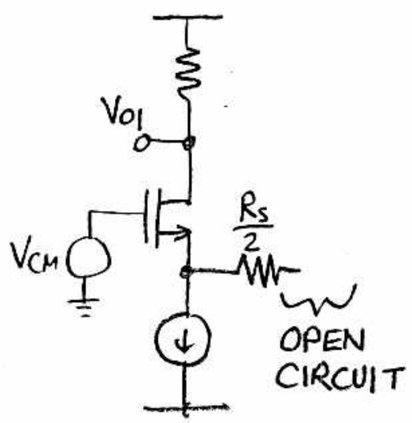


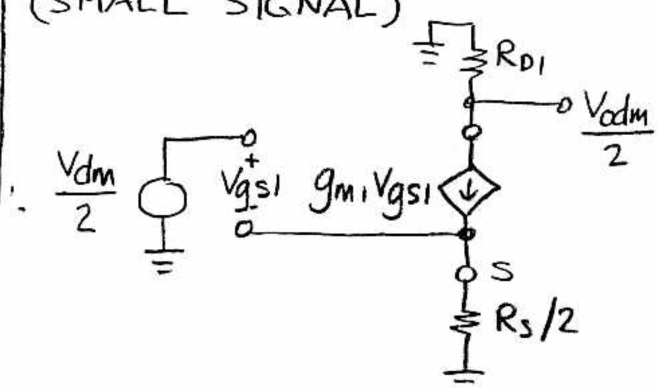
Figure 3.

COMMON MODE HALF CIRCUIT



NO CHANGE!

DIFFERENTIAL HALF CIRCUIT
(SMALL SIGNAL)



$$\frac{V_{dm}}{2} - V_{gs1} - \frac{g_{m1} V_{gs1} R_S}{2} = 0$$

$$\frac{V_{dm}}{2} = V_{gs1}\left(1 + \frac{g_{m1} R_S}{2}\right)$$

$$\frac{V_{odm}}{2} = -g_{m1} V_{gs1} R_{D1}$$

$$V_{gs1} = \frac{-V_{odm}}{2 g_{m1} R_{D1}} \longrightarrow \frac{V_{dm}}{2} = \frac{-V_{odm}}{2 g_{m1} R_{D1}}\left(1 + \frac{g_{m1} R_S}{2}\right)$$

$$\frac{V_{odm}}{V_{dm}} = \frac{-g_{m1} R_{D1}}{\left(1 + \frac{g_{m1} R_S}{2}\right)} = a_{vdm}$$

4. The Common Gate Amplifier, or "Trust the small-signal model, Luke"

The input impedance of the common source amplifier is (ideally) infinite, since the input voltage "sees" only the MOSFET gate terminal, which draws essentially no gate current due to the gate oxide. This high input impedance is usually an advantage, but in some high-frequency applications it is desired to have a relatively low input impedance. For example, in some RF circuit design applications, the amplifier input impedance can be used to match the characteristic impedance of a transmission line. Figure 4 shows the common gate amplifier, which is often used in this type of application.

You may assume that the substrate (body) terminal is tied to the source terminal. You may also assume channel length modulation to be negligible (λ=0).

Use the following MOSFET parameters for this process:

Parameter	N-channel	P-channel	Units
V_t	+1.10	-1.20	V
μC_{ox}	5.2E-5	1.5E-5	A/V^2

a) Show that the MOSFET is in the active region. [2]

b) Using the space on the following page, draw the low-frequency small-signal model for this amplifier circuit. [8]

c) Determine $|a_v|$, the magnitude of the low-frequency small-signal gain from v_{in} to v_{out}. Numerical value required! [4]

$$|a_v| = \left|\frac{v_{out}}{v_{in}}\right| = \underline{16.6}$$

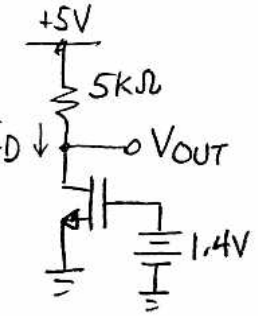
d) Is this amplifier inverting or noninverting? [2]

INVERTING **NONINVERTING**

e) Determine r_{in}, the small-signal input resistance looking into the amplifier input at the source terminal of the MOSFET. [4]

$r_{in} = \underline{302\,\Omega}$

LARGE SIGNAL DC BIAS



$$I_D = \frac{5.2E\text{-}5}{2}\,\frac{340}{1.6}(1.4-1.1)^2$$

$I_D = 497\,\mu A$

$V_{OUT} = 5V - (497\mu A)5k\Omega$

$V_{OUT} = 2.51V = V_{DS}$

$V_{GS} = 1.4V > V_t$ ✓

$V_{DS} = 2.51V > V_{eff}$ ✓

ACTIVE

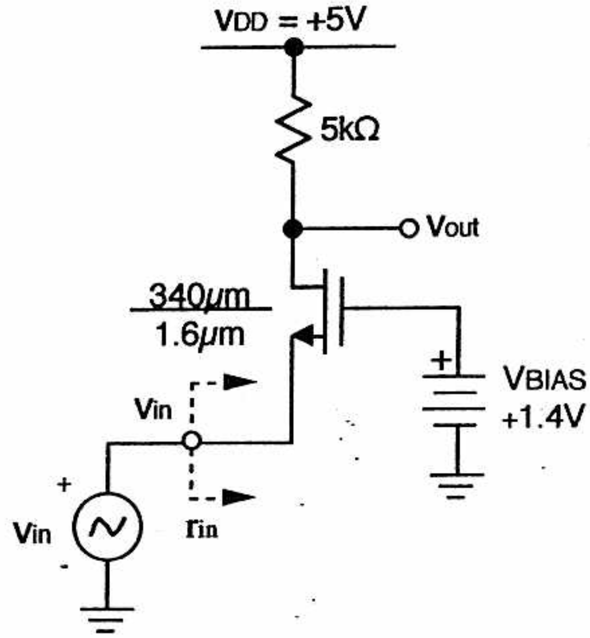
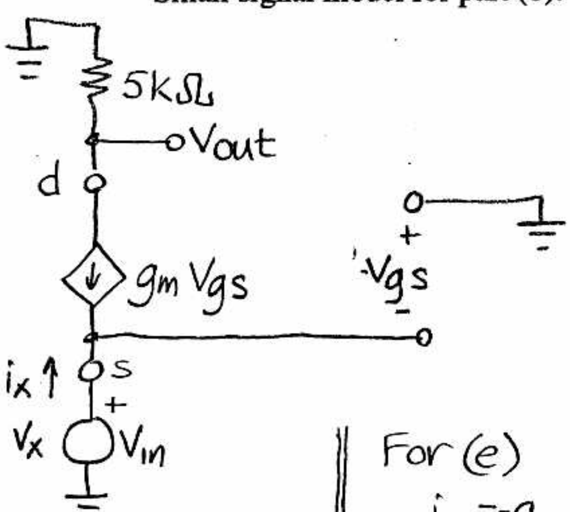


Figure 4.

Small signal model for part (b):



For (c)

KVL at output

$V_{out} = -g_m V_{gs}\, 5k\Omega$

KVL at input

$V_{in} = -V_{gs}$

$V_{out} = g_m V_{in}\, 5k\Omega$

$$\frac{V_{out}}{V_{in}} = g_m\, 5k\Omega = (3.31E\text{-}3)(5k\Omega) = 16.6$$

$$g_m = \frac{2(497\mu A)}{0.3V} = 3.31\, mA/V$$

For (e)

$$i_x = -g_m \underbrace{V_{gs}}_{-V_x} = g_m V_x$$

$$\frac{V_x}{i_x} = \frac{1}{g_m} = \frac{1}{3.31E\text{-}3} = 302\Omega$$