

Massachusetts Institute of Technology  
Department of Electrical Engineering and Computer Science

6.002 – Electronic Circuits  
Fall 2000

Lab 2: MOSFET Inverting Amplifiers & First-Order Circuits  
Handout F00-37

**Introduction**

This lab examines the behavior of an inverting MOSFET amplifier. It begins by examining the static input-output relation of the amplifier, and concludes by examining the dynamic behavior of the same amplifier when used as a digital logic inverter. You should complete the pre-lab exercises in your lab notebook before coming to lab. Then, carry out the in-lab exercises between October 23 and October 27. After completing the in-lab exercises, have a TA check your work and sign your lab notebook. Finally, complete the post-lab exercises in your lab notebook, and turn in your lab notebook on or before Friday November 3.

Bring in your favorite CD for In-Lab Exercise 2-3; it is meant to be a fun experiment and its results will not be needed for the post lab exercises.

**Pre-Lab Exercises**

- (2-1) Consider the inverting MOSFET amplifier shown in Figure 1. Using the SCS MOSFET model, write an expression for  $v_{OUT}$  as a function of  $v_{IN}$  for  $0 \leq v_{IN} \leq v_{OUT} + V_{TM}$ . Also, sketch and clearly label the form of  $v_{OUT}$  as a function of  $v_{IN}$  over the same range.

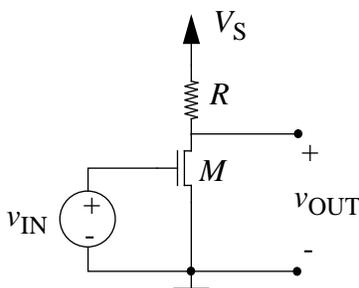


Figure 1: inverting MOSFET amplifier for Pre-Lab Exercises 2-1 and 2-2.

- (2-2) Write an expression for the small-signal gain of the MOSFET amplifier shown in Figure 1 assuming that its MOSFET is biased into saturated operation.
- (2-3) Consider the network shown in Figure 2. First, assume that  $v_{OUT} = 0$  at  $t = 0$ . Then, write an expression for  $v_{OUT}(t)$  for  $t \geq 0$  given that  $v_{IN}$  steps from 0 V to  $V_I$  at  $t = 0$ .
- (2-4) For the transient determined in Pre-Lab Exercise 2-3, determine the time at which  $v_{OUT}$  reaches a given  $V_T$  where  $0 < V_T < \frac{R_2}{R_1 + R_2} V_I$ .

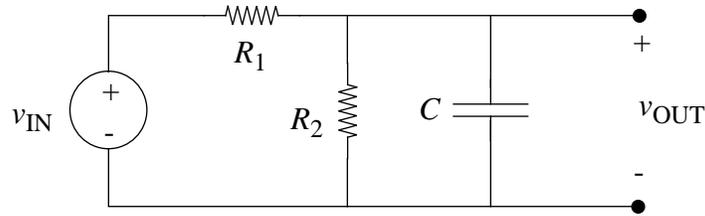


Figure 2: network for Pre-Lab Exercises 2-3 and 2-4.

### In-Lab Exercises

As part of the in-lab exercises, you will measure the threshold voltage and gate-to-source capacitance of a MOSFET. These parameters will be used to interpret the results of other in-lab exercises. Therefore, use the same MOSFET for the MOSFET labeled as  $M$  in every in-lab exercise described below.

- (2-1) This exercise measures the static input-output relation of the MOSFET amplifier shown in Figure 1. To begin, construct the amplifier as shown in Figure 3, and connect the signal generator and oscilloscope as shown. Next, set the signal generator to produce a 1-kHz sine wave with a peak-to-peak amplitude of 3 V and an offset of 1.5 V. Thus, the signal generator will produce a biased sine wave between 0 V and 3 V. Set the oscilloscope to operate in its X-Y mode with an X-axis (Channel #1) sensitivity of 500 mV per division and a Y-axis (Channels #2) sensitivity of 1 V per division. You should now see the input-output relation displayed on the oscilloscope. Finally, compare the displayed relation to that sketched in Pre-Lab Exercise 2-1.

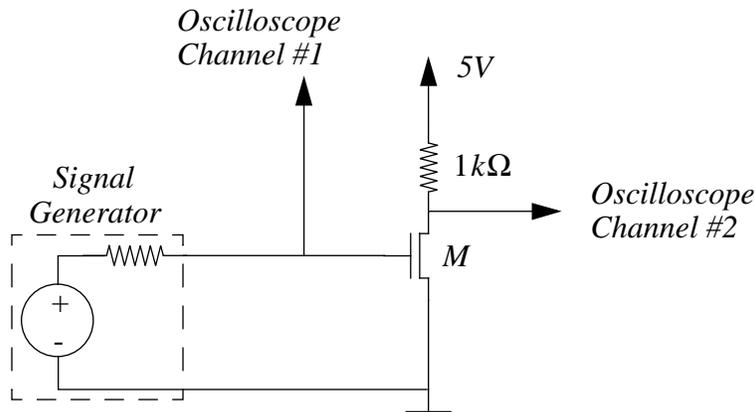


Figure 3: measuring the static input-output relation of the MOSFET amplifier shown in Figure 1.

Record the following data. First, record the value of  $v_{IN}$  above which  $v_{OUT}$  just begins to fall. This is the threshold voltage  $V_{TM}$  of the MOSFET; see the sketch from Pre-Lab Exercise 2-1. Second, record the values of  $v_{IN}$  which correspond to  $v_{OUT}$  values of 5 V, 4 V, 3 V, 2 V and 1 V. Alternatively, you may find it easier and much more accurate to use the signal generator as a programmable  $v_{IN}$  source and measure  $v_{OUT}$  with a multimeter.

- (2-2) This exercise measures the small-signal gain of the amplifier shown in Figure 1 when its output bias voltage is 2 V. To begin, construct Circuit #1 shown in Figure 4. Adjust the potentiometer until  $v_{OUT} = 2$  V as measured by the multimeter. Next, connect the

signal generator and the oscilloscope as shown in Circuit #2. Set the signal generator to zero and re-adjust the potentiometer so that  $v_{OUT} = 2$  V. Then, set the signal generator to produce an unbiased 1-kHz sine wave with a peak-to-peak amplitude of 100 mV. Measure the amplitude of both  $v_{in}$  and  $v_{out}$ , which are the sinusoidal components of  $v_{IN}$  and  $v_{OUT}$ , respectively; use AC coupling in Channel #1 of the oscilloscope to accurately measure  $v_{in}$ . The ratio of the amplitudes is the small-signal gain. Retain this circuit for the next exercise.

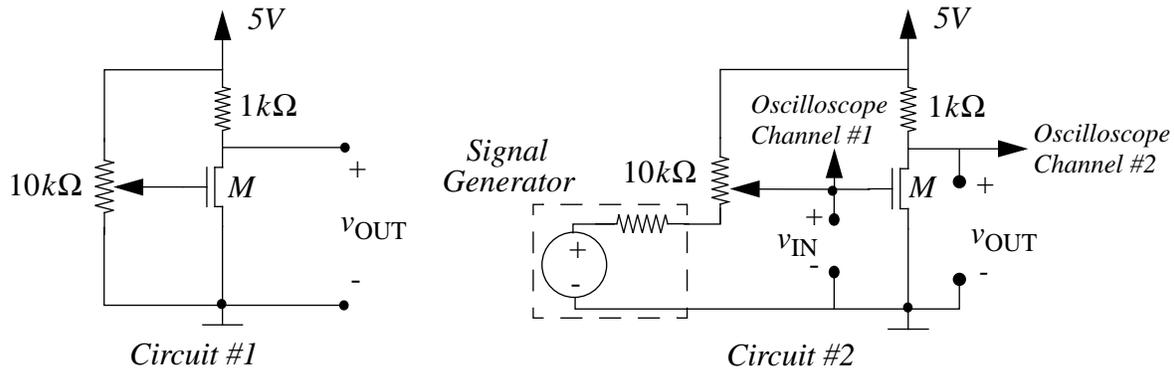


Figure 4: measuring the small-signal gain of the MOSFET amplifier.

- (2-3) The experiments in this exercise will use Circuit #2 constructed in In-Lab Exercise 2-2 to explore the limits of saturation operation of the amplifier by observing clipping of an output waveform and by listening to distortion in music output. Start by adjusting the input bias with the potentiometer, and observing the variation in  $v_{OUT}$ . Now, increase the peak-to-peak amplitude of the sine wave input from the signal generator to 300 mV. Observing the output on Channel #2 of the oscilloscope, increase the input bias voltage until you see clipping on the bottom part of the output. Use DC coupling in Channel #1 of the oscilloscope to make a note of the upper excursion limit of the voltage  $v_{IN}$ . Similarly, decrease the input bias voltage until you see clipping on the top part of the output, and make a note of the lower excursion limit of the voltage  $v_{IN}$ . These upper and lower limits of  $v_{IN}$  approximate the input operating limits of the amplifier.

Next, replace the signal generator with the CD player (use the headphones output). Set the CD player volume such that the peak-to-peak amplitude of the music signal  $v_{in}$  is approximately 300mV. Connect the  $v_{OUT}$  signal to an amplifying speaker (leave the oscilloscope connection in place) and adjust the speaker volume to listen to the music. Vary the input bias voltage with the potentiometer and listen to the change in volume. Observing  $v_{IN}$  on Channel #1 of the oscilloscope (using DC coupling), increase the input bias voltage till you begin to hear distortion. Is the upper excursion limit of the voltage  $v_{IN}$  at the onset of distortion approximately the same as that measured with the sine wave input? Now, decrease the input bias voltage till you begin to hear distortion. Is the lower excursion limit of the voltage  $v_{IN}$  at the onset of distortion approximately the same as that measured with the sine wave input?

The next two exercises will analyze the delay of the MOSFET amplifier when it is used as a digital logic inverter. Specifically, we will measure the delay of an inverter that is driving another inverter as illustrated in Figure 6.

- (2-4) Since the delay of an inverter is related to the capacitance of the node that is driven by

its output, this exercise measures the capacitance seen by the output of an inverter that is driving the gate of a MOSFET. First, construct the circuit shown in Figure 5. You will measure the capacitance  $C_P$  seen at node  $P$  in the circuit.  $C_P$  is the capacitance at node  $P$ , and includes  $C_{GS}$ , the gate capacitance of MOSFET  $M$ , in parallel with the oscilloscope input capacitance and a parasitic wiring capacitance. Set the signal generator to produce a 20-kHz square wave with an amplitude of 5 V peak-to-peak and an offset of 2.5 V. Channel #2 of the oscilloscope should display both a first-order rising step response and a first-order falling step response. Measure the time constant of the rising step response. Since the on resistance of the MOSFET is very small, the falling response has a very small time constant that is difficult to measure. Therefore, we will focus on the rising step response.

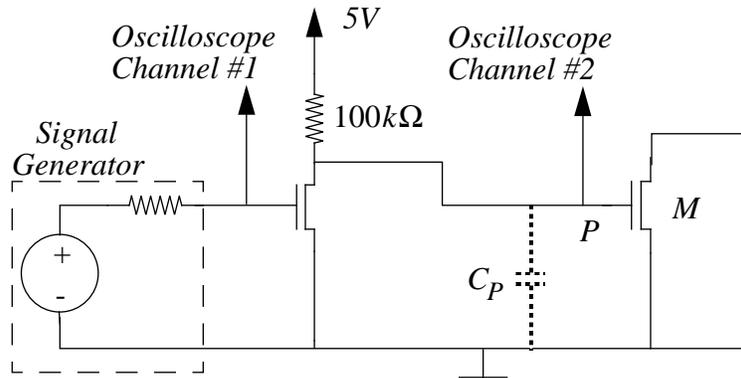


Figure 5: measuring the gate-to-source capacitance of the MOSFET amplifier.

- (2-5) This exercise measures the delay of the MOSFET amplifier when it is used as a digital logic inverter. Construct the circuit shown in Figure 6; As in the previous exercise, set the signal generator to produce a 20-kHz square wave with an amplitude of 5 V peak-to-peak and an offset of 2.5 V. Finally, use the oscilloscope to measure the delay from the time at which the signal generator switches low (Channel #1) to the time at which the inverter pair output (Channel #2) begins to switch low. (Note that a high to low transition of the signal generator corresponds to a rising transition at the node  $P$ ).

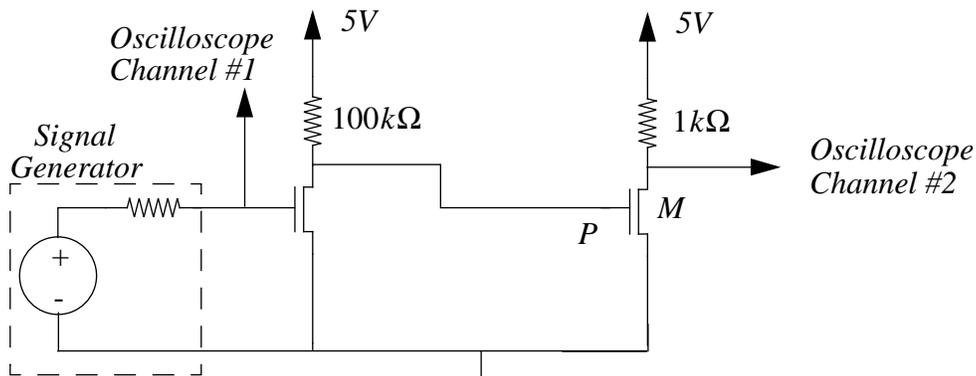


Figure 6: measuring the delay of the MOSFET amplifier when it is used as a digital logic gate.

## Post-Lab Exercises

- (2-1) This exercise examines how well the MOSFET amplifier model developed during Pre-Lab Exercise 2-1 explains the input-output relation measured during In-Lab Exercise 2-1. The model contains four parameters which are required to numerically evaluate the input-output relation:  $V_S$ ,  $R$ ,  $V_{TM}$  and  $K$ . From Figure 3,  $V_S = 5$  V and  $R = 1$  k $\Omega$ . Further,  $V_{TM}$  was measured during In-Lab Exercise 2-1. Thus, only  $K$  is unknown. Use the value of  $v_{IN}$  recorded for  $v_{OUT} = 1$  V to determine  $K$ . Then, use the numerical parameters and the model to graph  $v_{OUT}$  as a function of  $v_{IN}$  for  $1$  V  $\leq v_{OUT} \leq 5$  V. *Note: You are encouraged, although not required, to use Matlab to plot the graph. See the Matlab handout at the end of the lab packet.* On this graph, also plot the data measured during In-Lab Exercise 2-1. How well does the model explain the data?
- (2-2) From the data recorded during In-Lab Exercise 2-2, compute the small-signal gain of the amplifier for  $v_{OUT} = 2$  V. From the data recorded during In-Lab Exercise 2-1, again compute the small-signal gain by estimating the slope of the input-output relation at  $v_{OUT} = 2$  V. Finally, compute the small-signal gain from the analysis of Pre-Lab Exercise 2-2 using the parameters determined during Post-Lab Exercise 2-1. Do the three gains match well?
- (2-3) Figure 2 models the behavior of node  $P$  in Figure 5 when the MOSFET of the first inverter stage is off:  $R_1$  is the 100 k $\Omega$  resistor;  $R_2$  models the oscilloscope input resistance; and  $C$  models  $C_P$ . Recall  $C_P$  is the capacitance of node  $P$ , and includes  $C_{GS}$ , the gate capacitance of MOSFET  $M$ , in parallel with the oscilloscope input capacitance and a parasitic wiring capacitance. Assume that the oscilloscope input resistance and capacitance are 100 M $\Omega$  and 10 pF, respectively. Combine the analysis of Pre-Lab Exercise 2-3 and the time constant measured during In-Lab Exercise 2-4 to determine  $C_P$ .
- (2-4) With  $V_I = 5$  V and  $V_T = v_T$ , the analysis of Pre-Lab Exercise 2-4 models the delay measured during In-Lab Exercise 2-5. Using the parameters computed during Post-Lab Exercise 2-3, predict the delay and compare the prediction to the measurement. Note that the oscilloscope with its input resistance and capacitance were not connected to the MOSFET gate at node  $P$  when the delay was measured; see Figure 6.

## Using MATLAB for Lab 2

You are encouraged, although not required, to use Matlab to plot the graph in Post-Lab Exercise 2-1. *Note: This document is provided specifically for this exercise. There are a number of resources for general help with Matlab on Athena. See <http://web.mit.edu/olh/Matlab/>.* To use Matlab, you must first type “add matlab” at the Athena prompt, and then invoke Matlab by typing the command “matlab” at the Athena prompt.

Start by entering the the values for  $V_S$ ,  $R$ ,  $V_{TM}$  and  $K$ .

```
VS = 5;  
R = 1000;  
VTM = whatever value you measured during In-Lab Exercise 2-1;  
K = whatever value you computed for K;
```

Your ultimate goal is to generate a plot of  $v_{OUT}$  as a function of  $v_{IN}$  for  $1\text{ V} \leq v_{OUT} \leq 5\text{ V}$ . In In-Lab exercise 2-1, you measured  $v_{IN}$  for  $v_{OUT} = 1\text{V}$ . You will now use this value of  $v_{IN}$  to generate a vector  $\mathbf{v}_{IN}$  of evenly spaced values between  $V_{TM}$  and the value of  $v_{IN}$  for which  $v_{OUT} = 1\text{V}$ .

```
 $\mathbf{v}_{IN} = \text{linspace}(\text{VTM}, \text{value measured for } v_{IN} \text{ when } v_{OUT} = 1\text{V}, 50);$ 
```

Type “help linspace” at the matlab prompt for details on the linspace command. Next you want to generate a vector  $\mathbf{v}_{OUT}$  of output voltages corresponding the the input voltages in  $\mathbf{v}_{IN}$ . To do this, you will use the expression for  $v_{OUT}$  as a function of  $v_{IN}$  that you came up with in Pre-Lab exercise (2-1).

```
 $\mathbf{v}_{OUT} = \text{VS} - 0.5 * \text{R} * \text{K} * (\mathbf{v}_{IN} - \text{VTM}).^2;$ 
```

Now you should have two vectors,  $\mathbf{v}_{IN}$  and  $\mathbf{v}_{OUT}$ , that you can use to plot the input-output characteristics of your MOSFET in saturation. Now use the “plot” command to generate a plot.

```
plot( $\mathbf{v}_{IN}$ ,  $\mathbf{v}_{OUT}$ );
```

You should note that  $v_{OUT} = 5\text{V}$  for  $v_{IN} \leq V_{TM}$ . To include this in the plot, you need one more data point.

```
plot([0  $\mathbf{v}_{IN}$ ], [5  $\mathbf{v}_{OUT}$ ]);
```

The above command will append the data point (0,5) to the plot.

Now you are done. You may want to use other commands to better format your graph. Try the commands “title”, “xlabel”, “ylabel”, “axis”, and “grid”. For help with any matlab command, type “help [command]” at the Matlab prompt.