

Massachusetts Institute of Technology  
Department of Electrical Engineering and Computer Science

6.002 – Circuits & Electronics  
Spring 2004

Lab #2: MOSFET Inverting Amplifiers & First-Order Circuits

**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 on your assigned lab day between March 15 and March 19. After completing the in-lab exercises, have a TA or LA 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 Wednesday March 31.

**Pre-Lab Exercises**

- (2-1) Consider the inverting MOSFET amplifier shown in Figure 1. Using the SCS MOSFET model, derive an expression for  $v_{\text{OUT}}$  as a function of  $v_{\text{IN}}$  for  $0 \leq v_{\text{IN}} \leq v_{\text{OUT}} + V_T$ . Also, qualitatively sketch and clearly label  $v_{\text{OUT}}$  as a function of  $v_{\text{IN}}$  over the same range.
- (2-2) Derive 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  $v_{\text{OUT}} = 0$  at  $t = 0$ . Then, derive an expression for  $v_{\text{OUT}}(t)$  for  $t \geq 0$  given that  $v_{\text{IN}}$  steps from 0 V to  $V_I$  at  $t = 0$ . Second, assume that  $v_{\text{OUT}} = \frac{R_2}{R_1+R_2}V_I$  at  $t = 0$ . Then, derive an expression for  $v_{\text{OUT}}(t)$  for  $t \geq 0$  given that  $v_{\text{IN}}$  steps from  $V_I$  to 0 V at  $t = 0$ .
- (2-4) For both transients determined in Pre-Lab Exercise 2-3, determine the time at which  $v_{\text{OUT}}$  reaches a given threshold voltage  $\bar{V}_T$  where  $0 < \bar{V}_T < \frac{R_2}{R_1+R_2}V_I$ .

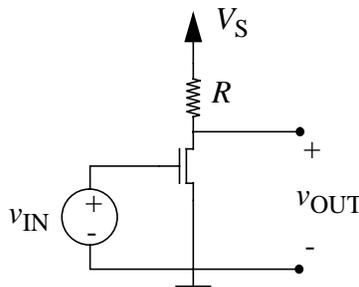


Figure 1: inverting MOSFET amplifier for Pre-Lab Exercises 2-1 and 2-2.

## In-Lab Exercises

As part of the in-lab exercises, you will measure the threshold voltage and gate-to-source capacitance  $C_{GS}$  of a MOSFET. These parameters will be used to interpret the results of other in-lab exercises. Therefore, use the same MOSFET in every in-lab exercise described below. Remember, the MOSFET should be labeled “2N7000”.

- (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 (Channel #2) sensitivity of 1 V per division. To set the oscilloscope to operate in its X-Y mode, turn the horizontal sweep (SEC/DIV) knob all the way counterclockwise. You should now see the input-output relation displayed on the oscilloscope. Compare the displayed relation to that sketched in Pre-Lab Exercise 2-1.

In your lab notebook, sketch the input-output relation as displayed on the oscilloscope, and record the following data. First, record the value of  $v_{IN}$  above which  $v_{OUT}$  just begins to fall. This is the threshold voltage  $V_T$  of the MOSFET; see your sketch from Pre-Lab Exercise 2-1. Second, record the values of  $v_{IN}$  which yield  $v_{OUT}$  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 source of constant  $v_{IN}$  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

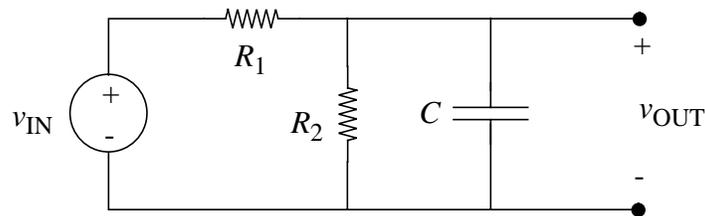


Figure 2: network for Pre-Lab Exercises 2-3 and 2-4.

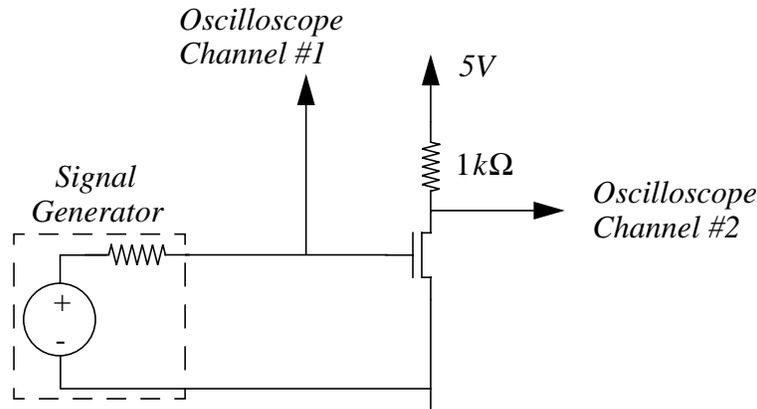


Figure 3: measuring the static input-output relation of the MOSFET amplifier shown in Figure 1.

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. With the signal generator amplitude set to zero, adjust the potentiometer again until  $v_{OUT} = 2$  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.

- (2-3) Adjust the input bias with the potentiometer, and observe the variation in  $v_{OUT}$ . Next, 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 MOSFET bias voltage using the potentiometer until you see clipping on the lower part of the output waveform. Use DC coupling in Channel #1 of the oscilloscope, and make a note of the upper excursion limit of the corresponding input voltage  $v_{IN}$ . Similarly, decrease the input bias voltage until you see clipping on the upper part of the output waveform, and make a note of the lower excursion limit of the corresponding input voltage  $v_{IN}$ . These upper and lower limits of  $v_{IN}$  approximate the useful input operating limits of the amplifier.
- (2-4) This exercise measures the gate-to-source capacitance  $C_{GS}$  of the MOSFET. First, construct the circuit shown in Figure 5. 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. The oscilloscope should display a first-order step response. Measure the time constant of that step response. Second, remove the MOSFET from the circuit, and measure the time constant again.

The first time constant that you measure is a consequence of the parallel combination of the MOSFET gate capacitance  $C_{GS}$ , the oscilloscope probe capacitance, and any parasitic wiring capacitance. The second time constant is a consequence of only the parallel combination of the oscilloscope probe capacitance, and the parasitic wiring capacitance. Thus, from these two time constants it is possible to determine  $C_{GS}$ .

- (2-5) This exercise measures the delay of the MOSFET amplifier shown in Figure 1 when it is used as a digital logic inverter. Construct the circuit shown in Figure 6; the 100-k $\Omega$  resistor in this circuit models the Thevenin resistance of whatever drives the inverter. Next, connect the oscilloscope and signal generator as shown. 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

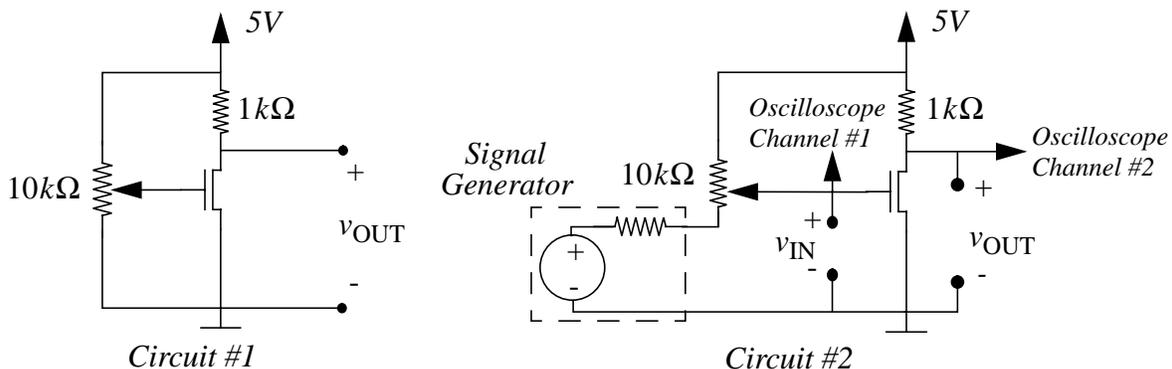


Figure 4: measuring the small-signal gain of the MOSFET amplifier.

oscilloscope to measure the delay from the time at which the signal generator switches high to the time at which the inverter output begins to switch low. Also, measure the delay from the time at which the signal generator switches low to the time at which the inverter output begins to switch high. Since the output of the inverter begins to switch when the MOSFET gate voltage passes by  $V_T$ , the two delays may not be the same; see Pre-Lab Exercise 2-4.

### 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:  $V_S$ ,  $R$ ,  $V_T$  and  $K$ . From Figure 3,  $V_S = 5\text{ V}$  and  $R = 1\text{ k}\Omega$ . Further,  $V_T$  was measured during In-Lab Exercise 2-1. Thus, only  $K$  is unknown. Use the value of  $v_{IN}$  recorded for  $v_{OUT} = 1\text{ V}$  to determine  $K$ . Then, use the numerical parameters and the model to graph  $v_{OUT}$  as a function of  $v_{IN}$  for  $1\text{ V} \leq v_{OUT} \leq 5\text{ V}$ . On this graph, also plot the data measured during In-Lab Exercise 2-1. How well does the model explain the data?

*You are encouraged, but not required, to use MatLab to graph  $v_{OUT}$  as a function of  $v_{IN}$ . To do so, see the MatLab section at the end of this lab assignment.*

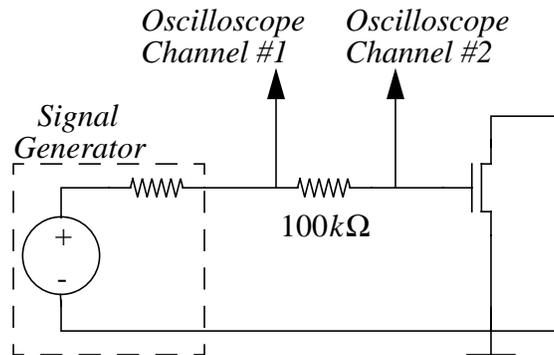


Figure 5: measuring the gate-to-source capacitance of the MOSFET amplifier.

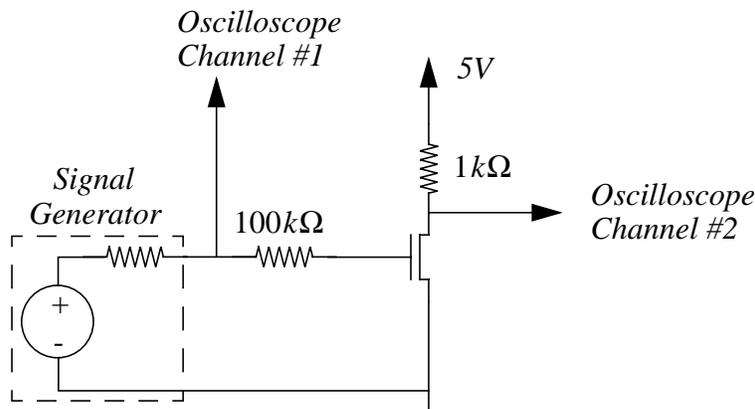


Figure 6: measuring the delay of the MOSFET amplifier shown in Figure 1 when it is used as a digital logic gate.

- (2-2) From the data recorded during In-Lab Exercise 2-2, compute the small-signal gain of the amplifier for  $v_{\text{OUT}} = 2 \text{ V}$ . 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  $v_{\text{OUT}} = 2 \text{ V}$ . 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 circuit shown in Figure 5:  $R_1$  models the generator source resistance and the 100-k $\Omega$  resistor;  $R_2$  models the oscilloscope probe resistance; and  $C$  models  $C_{\text{GS}}$  (if present) in parallel with the oscilloscope probe capacitance and any parasitic wiring capacitance. Assume that the oscilloscope probe resistance and capacitance are 100 M $\Omega$  and 10 pF, respectively. Combine the analysis of Pre-Lab Exercise 2-3 and the time constants measured during In-Lab Exercise 2-4 to determine  $C_{\text{GS}}$  and the wiring capacitance.
- (2-4) With  $V_1 = 5 \text{ V}$  and  $\bar{V}_T = V_T$ , the analysis of Pre-Lab Exercise 2-4 models the delays measured during In-Lab Exercise 2-5. Using the parameters computed during Post-Lab Exercise 2-3, predict the delays and compare the predictions to the measurements. Note that the oscilloscope probe, with its resistance and capacitance, was not connected to the MOSFET gate when the delays were measured; see Figure 6.

### Using MatLab For Post-Lab Exercise 2-1

This section is provided specifically to help with Post-Lab Exercise 2-1. There are many resources for general help with MatLab on Athena; see <http://web.mit.edu/olh/matlab/>.

To use MatLab, first type `add matlab` at the Athena prompt, and then invoke MatLab by typing the command `matlab` at the Athena prompt. A MatLab window will then appear. Do all your work inside this window by typing commands followed by a return. When you are finished, type `quit` to quit MatLab.

To begin, define and enter the values for  $V_S$ ,  $R$ ,  $V_T$  and  $K$  by typing

```
VS = 5;
R = 1000;
VT = the threshold voltage you measured during In-Lab Exercise 2-1;
K = the value for K you computed during Post-Lab Exercise 2-1;
```

The semicolon at the end of each command instructs MatLab not to echo the result of the command. You may omit the semicolon if you wish. To see the value of a variable that you have defined, type the variable name with no assignment.

The ultimate goal here is to generate a graph of  $v_{\text{OUT}}$  as a function of  $v_{\text{IN}}$  for  $1 \text{ V} \leq v_{\text{OUT}} \leq 5 \text{ V}$ . To do so, you must create a vector of  $v_{\text{IN}}$  values and a vector of  $v_{\text{OUT}}$  values that can be plotted against one another. During In-Lab Exercise 2-1, you measured  $v_{\text{IN}}$  for  $v_{\text{OUT}} = 1 \text{ V}$ . You will now use that value of  $v_{\text{IN}}$  to generate a row vector `vIN` of evenly spaced values between  $V_T$  and the value of  $v_{\text{IN}}$  for which  $v_{\text{OUT}} = 1 \text{ V}$ . To do so, type

```
vIN = linspace(VT , the value you measured for vIN when vOUT = 1 V , 50);
```

Type `help linspace` for details concerning the `linspace` command. Next you must generate a row vector `vOUT` of output voltages that correspond to the input voltages in `vIN`. To do this, use the expression for  $v_{\text{OUT}}$  as a function of  $v_{\text{IN}}$  that you derived in Pre-Lab Exercise 2-1. Thus, type

```
vOUT = VS - 0.5 * R * K * (vIN - VT).^2;
```

You should now have two row vectors, `vIN` and `vOUT`, that you can use to graph the input-output relation of your MOSFET amplifier operating with the MOSFET in saturation. To do so, use the `plot` command to generate a graph by typing

```
plot(vIN,vOUT)
```

For the cutoff region of the MOSFET operation,  $v_{IN} \leq V_T$ , and  $v_{OUT} = 5V$ . To include this in the graph, you need one more data point. To include that data point, type

```
plot([0 vIN],[5 vOUT])
```

The above `plot` command appends the data point (0,5) to the graph. You are now done. You may want to use other commands to better format your graph. Try the commands `title`, `xlabel`, `ylabel`, `axis`, and `grid on`. For help with any MatLab command, type `help` followed by the command name. To print your graph, click on the printer symbol on the graphics window produced by the `plot` command, and direct the printout to the nearest Athena printer.