LAB 7

MOSFET CHARACTERISTICS AND APPLICATIONS

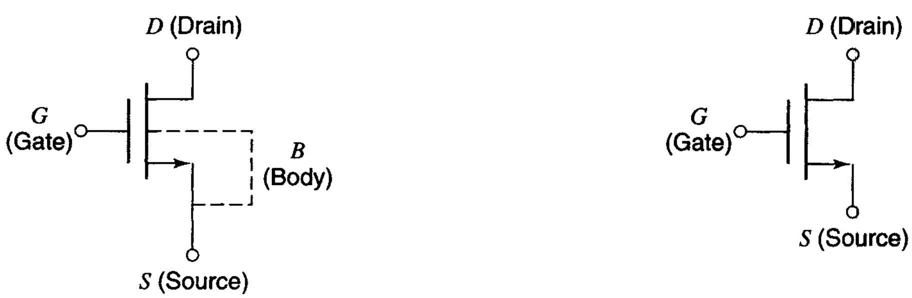
Objective

In this experiment you will study the i-v characteristics of an MOS transistor. You will use the MOSFET as a variable resistor and as a switch.

BACKGROUND

The MOS (metal-oxide- semiconductor) transistor (or MOSFET) is the basic building block of most computer chips, as well as of chips that include analog and digital circuits. In this lab, we will work with what is called an n-channel MOS transistor. The internal structure and operation of this device, as well as of its complement, the p-channel MOSFET are studied in semiconductor device courses. Here we will concern ourselves only with external i-v behavior.

A common symbol for the n-channel MOS transistor is shown in Fig. 1(a). Of the terminals shown, the ones we will focus on are the source, the drain, and the gate. In the transistor we will be working with in this lab, the fourth terminal, labeled body in Fig. 1(a), is not accessible externally; rather, it is internally connected to the source, as shown by the broken line. For simplicity, then, we will use the symbol shown in Fig. 1 (b).



(a) (b)

Figure 1. MOSFET transistor

To study the MOS transistor, we can connect two external voltage sources to it, as shown in Fig. 2. These provide the drain-source voltage v_{DS} and the gate-source voltage v_{GS}. The voltage v_{DS} may cause a drain-to-source current i_{DS} as shown, provided that there is a path for this current from the drain (through the device) to the source. Whether such a path exists or not depends on the value of v_{GS}. For small values of v_{GS}, no such path is established within the device, and i_{DS} is zero. The device then looks like an open circuit between the drain and the source. For a sufficiently high v_{GS}, an internal current path, called a channel, is established between the drain and the source.[1] Now a current i_{DS} can flow. The precise value of v_{GS} determines how easy it is for the channel to conduct the current; the higher the v_{GS} value, the easier such conduction is and the larger the value of i_{DS}, other things being equal. For a given v_{GS}, the value of i_{DS} will also depend on v_{DS} and will tend to increase with the latter.

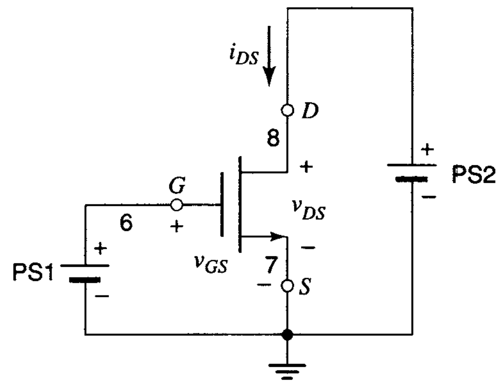


Figure 2

MOSFET I-V CHARACTERISTICS

1. Hook up the circuit of Fig. 2. This circuit will be used in the following steps to investigate the i-v characteristics of the n-channel MOSFET. The chip used in this experiment is a CD4007, containing six MOSFETs. We will use only one of them, as shown in the pin assignment in Fig. 3.

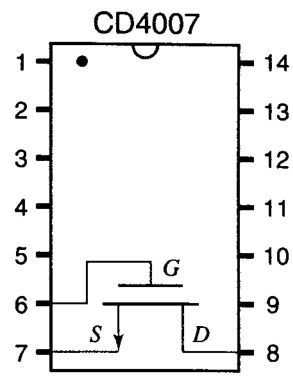


Figure 3

2. Set v_{GS} = 5 V Measure the drain current i_{DS}, versus the drain-source voltage, v_{DS}, from 0 to 5 V Make sure you take measurements at a sufficient number of v_{DS} values since you will later need to plot i_{DS} versus v_{DS}. Include a point at v_{DS} = 0.1 V for later use.

3. Repeat the entire step 2 for v_{GS} = 3 V and v_{DS} = 1 V.

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[1] It should be noted that the only DC current in the device is the drain-to-source current iDS. The gate is internally separated by an insulator from the channel, so the gate current is practically zero.

4. With v_{DS} = 5 V, determine the value of v_{GS} at which the current i_{DS} becomes negligible; assume that for our purposes this means 5mA. This value of v_{GS} is close to the so-called threshold voltage of the transistor, and it is positive for an "enhancement mode" MOSFET, which is what we are working with here.[2]

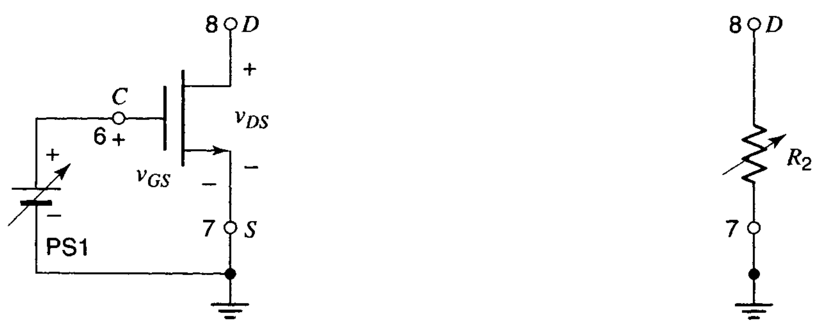
5. Using the data you have collected in steps 2 and 3, plot a family of curves for the drain current, i_{DS}, versus the drain-source voltage, v_{DS} from 0 to 5 V, with v_{GS} as a parameter. Use a single set of v_{DS} - i_{DS} axes for this plot. There should be one curve for each v_{GS} value (1 V, 3 V, and 5 V) on this family of curves. Label each curve with the corresponding v_{GS} value.

6. You should be able to observe on the above plot that, for each curve, the current tends to a constant (or, as we say, saturates) as v_{DS} is made large. What is, approximately, the saturation value of the current for each of the three v_{GS} values?

THE MOSFET AS A VOLTAGE-CONTROLLED RESISTOR

7. Verify that the curves obtained in step 5 pass through the origin and that their shape is nearly a straight line for sufficiently small v_{DS} values. Thus, in that region i_{DS} is approximately proportional to $v_{DS,}$ and Ohm's law is approximately satisfied; that is, we have a nearly linear resistor. The resistance R = v_{DS}/i_{DS} is given by the inverse of the slope of the curves near v_{DS} = 0. Since the slope depends on v_{GS}, the latter can be used to control the resistance value. Determine this resistance graphically for v_{GS} values of 5 V, 3 V, and 1 V

8. Form the circuit of Fig. 4(a), by disconnecting PS#2 and the DMMs from the circuit of Fig. 2. Connect an ohmmeter between the drain and the source, and verify that the resistance across these two terminals can be varied by varying v_{GS}. Verify the values you calculated in step 7. Also, determine the resistance when v_{GS} = 0. When finished with this part, disconnect the ohmmeter from the circuit.



(a) (b)

Figure 4

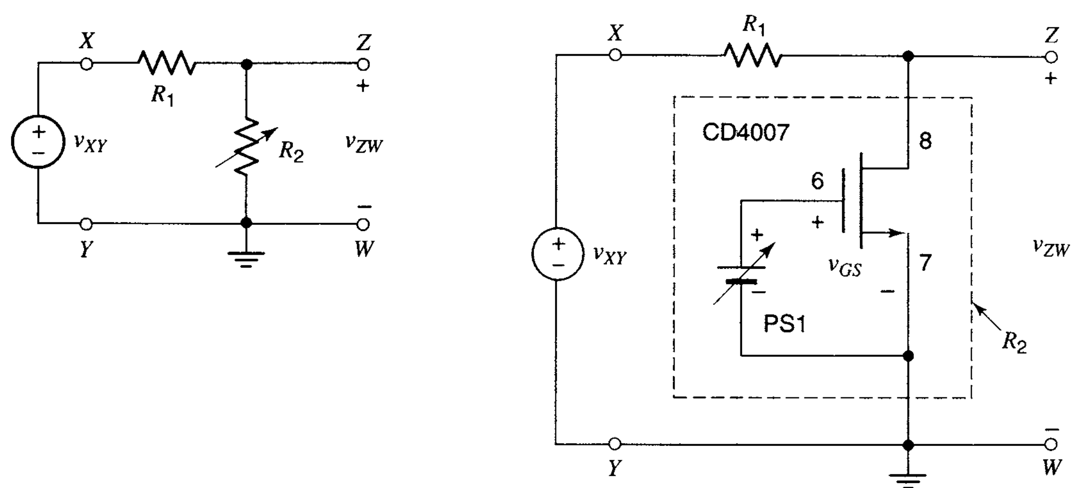
[2] Another variety is the depletion-mode MOSFET, for which the threshold voltage is negative. We will not be using depletion-mode MOSFETs in this lab.

From the results so far, it is evident that the circuit of Fig. 4(a) is a voltage controlled resistor; that is, it is equivalent to Fig. 4(b), where the value of R2 depends on v_{GS}. The arrow through the resistor indicates that its resistance can be varied. (Keep in mind that this resistor is linear provided that the drain-source voltage is kept sufficiently small; otherwise, its current will not be proportional to the voltage across it.)

9. You can use the fact that the MOSFET can be used as a voltage-controlled resistor, to make a voltage-controlled potentiometer. Consider the voltage divider shown in Fig. 5(a). R_1 is a conventional, fixed resistor, whereas R_2 is a variable resistor. If a voltage v_{XY} is applied to the circuit as shown, the output voltage v_{ZW} will be

$$v_{ZW} = \frac{R_2}{R_1 + R_2} v_{XY}$$

In the circuit of Fig. 5(a), R_2 can be replaced by the MOSFET, as suggested by the equivalence of the circuits in Figs. 4(a) and 4(b). Thus, the circuit of Fig. 5(b) results (do not build this circuit yet). Now, one can vary the division ratio $R_2/(R_1 + R_2)$ by varying R_2 through v_{GS}.



(a) (b)

Figure 5

Based on your results from steps 7 and 8, calculate a value to be used for R, so that the voltage division ratio, $R_2/(R_1 + R_2)$, can be varied from the value of 1 to a value of about 0.1, as v_{GS} is varied from 0 to 5 V

9. Now build the circuit of Fig. 5(b). Keep in mind that the MOSFET behaves as a linear resistor only if the voltage between its drain and source is sufficiently small; thus, avoid large v_{ZW} values. Do not use an ohmmeter in this step. Verify that the voltage division ratio, $v_{ZW}/v_{XY} = R_2/(R_1 + R_2)$, can be varied in the range expected from step 9 by varying v_{GS}.

THE MOSFET AS A SWITCH

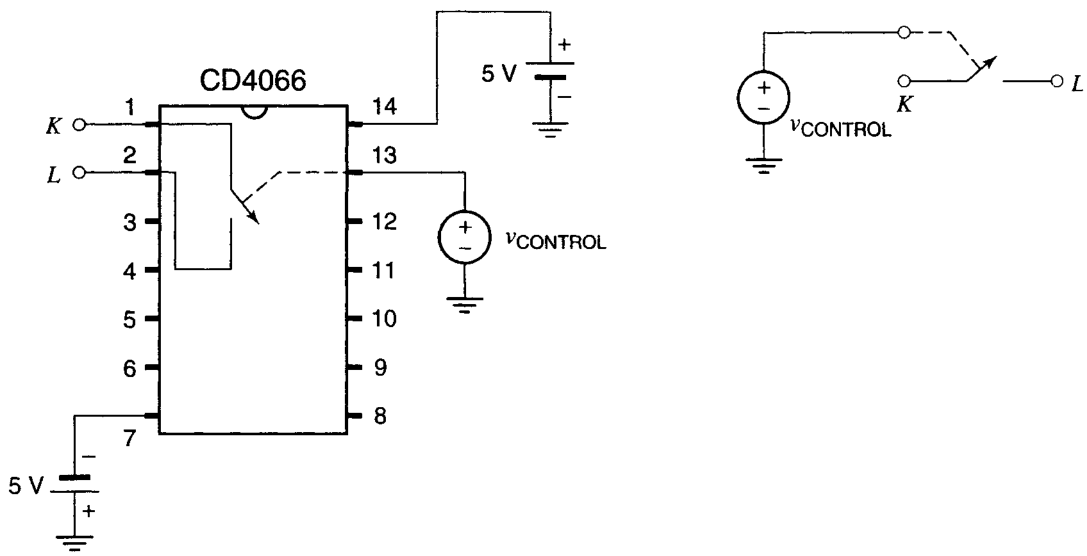
11. From the results obtained so far, you can see that if v_{GS} is sufficiently small, the MOSFET behaves as an open circuit between the drain and the source; thus, the drain-source path in Fig. 4 acts as an open switch in this case. Also, you can see that with v_{GS} large, the MOSFET presents a rather small resistance between the source and the drain (always assuming that the. drain-source voltage is small). If that resistance were zero, the MOSFET would behave as a closed ideal switch in this case; since the resistance is not zero, we can say that it behaves as a closed nonideal switch (essentially, it behaves as a closed ideal switch with some resistance in series with it).

    Thus, the MOSFET can be viewed as a voltage-controlled switch; the switch closes if v_{GS} is made large and opens if v_{GS} is made small.

12. The resistance of the closed MOSFET switch above is significant because the MOSFETs on the chip used in the above steps are not meant to operate as switches per se. There are other chips which are explicitly designed for this purpose. They contain transistors designed to have a small resistance when the magnitude of their v_{GS} is large.[3] Such chips also contain internal circuitry that develops the proper vGS values for turning the switch on or off, depending on the value of an external control voltage supplied by the user. You will now use such a chip.

13. The chip we will be working with is the CD4066 or equivalent type, which contains four switches. The pin assignment for the switch we will be using is shown in Fig. 6(a). Connect the chip as shown, but do not turn on the power yet. The switch will close if an externally applied control voltage $v_{CONTROL}$ is made high, and it will open if the control voltage is made low (do not test this yet). This behavior is indicated schematically in Fig. 6(b); in this figure, the ±5 V power supply connections in Fig. 6(a) are not shown, but keep in mind that they are required for the switch to operate.

[3] To maintain this low resistance even when their terminal voltages vary considerably, two MOSFETs inside such chips (one n-channel and one p-channel) are connected in parallel to form a switch. You do not need to concern yourself with this at this time.



(a) (b)

Figure 6

14. Verify the behavior described in the previous step by using the connection indicated in Fig. 7. Ground terminal K, and measure the resistance between terminal L and ground with an ohmmeter. Usea control voltage $v_{CONTROL}$ of 2 V to close the switch, and -2 V to open it. What are the corresponding resistance values? Can they reasonably be thought to correspond to a short and an open circuit, respectively?

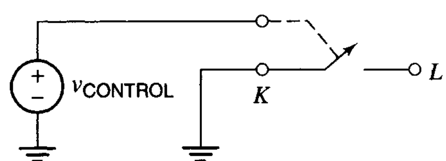
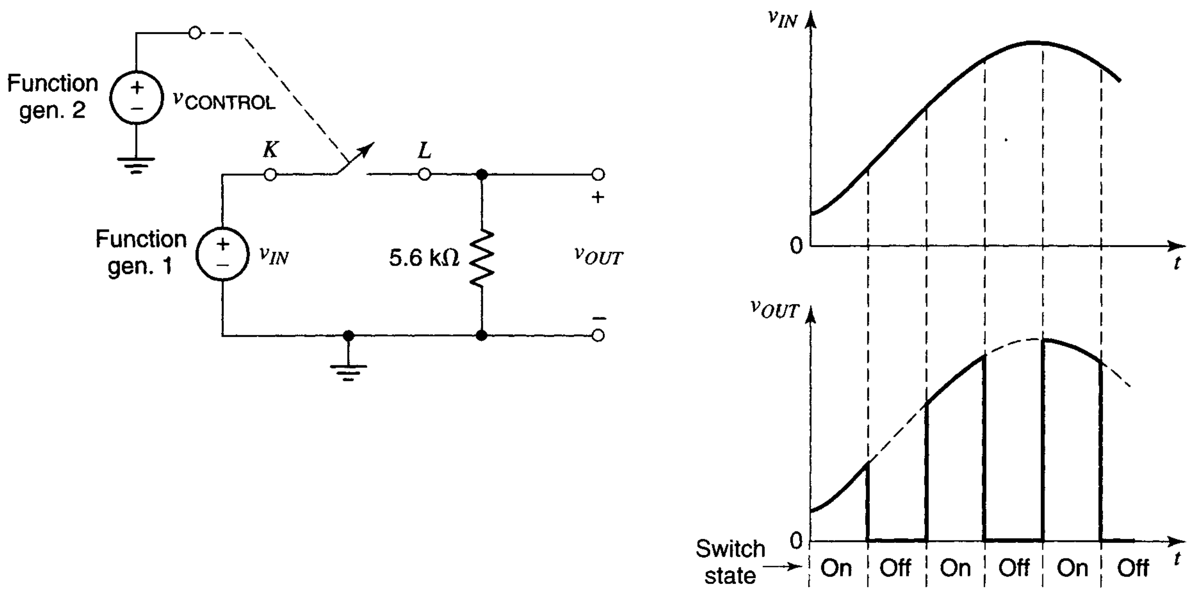


Figure 7

A CHOPPER

15. The circuit in Fig. 8(a) is called a *chopper*, and is used in communications and instrumentation. When the switch is closed, the output is connected to the input and v_{OUT} is equal to v_{IN}; when the switch is open, the output is disconnected from the input and v_{OUT} equals zero. This operation is illustrated in Fig. 8(b).



(a) (b)

Figure 8

Assume that the input voltage is a 1 kHz sinusoidal voltage with an amplitude of 1 V and that the control voltage is a 10 kHz square wave, taking values +2 V and - 2 V. Without connecting the circuit, sketch the expected waveform at the output, based on the behavior you observed in the previous step.

16. Now connect the circuit of Fig. 8(a), using the values given in the previous step. Be sure the power supplies are connected as has been shown in Fig. 6(a) and are turned on. You will need two function generators. Use the scope to adjust the generator that provides the control voltage, so that it is a 10 kHz square wave with values - 2 V and 2 V at its peaks and bottoms, respectively (if your generator does not provide such large values, smaller values can be tried). Then, use the scope's channel 1 to observe the input voltage (a 1 kHz sinusoidal voltage with a 1 V amplitude) and channel 2 to observe the output voltage. Trigger from channel 1. You will need to adjust slowly and very carefully the frequency of the control voltage generator to get a stable display. This adjustment may be tricky. Verify that the output waveform. is as expected in step 15.

A TRACK-AND-HOLD CIRCUIT

17. Consider the circuit of Fig. 9(a). It operates as follows:
    (a) When the switch is closed, the output is equal to the input (i.e., the output tracks the input).
    (b) When the switch is opened, the voltage on the capacitor cannot change anymore and remains at the value it had at the moment the switch opened.

    This operation is illustrated in Fig. 9(b). As seen, when the switch is opened the capacitor holds the above value until the switch closes again, at which point the output again becomes equal to the input and tracks it. This is a track-and-hold circuit. It has many uses;

for example, it is found at the input of analog-to-digital converters; during the intervals that the track-and-hold's output is held constant, the converter processes it to convert it to a digital code. This code can then be fed to a computer, to a digital communications link for transmission, or to a digital signal processor for further processing. Analog-to-digital converters are used, for example, in recording studios to convert music signals to digital words, which can then be stored on compact discs.

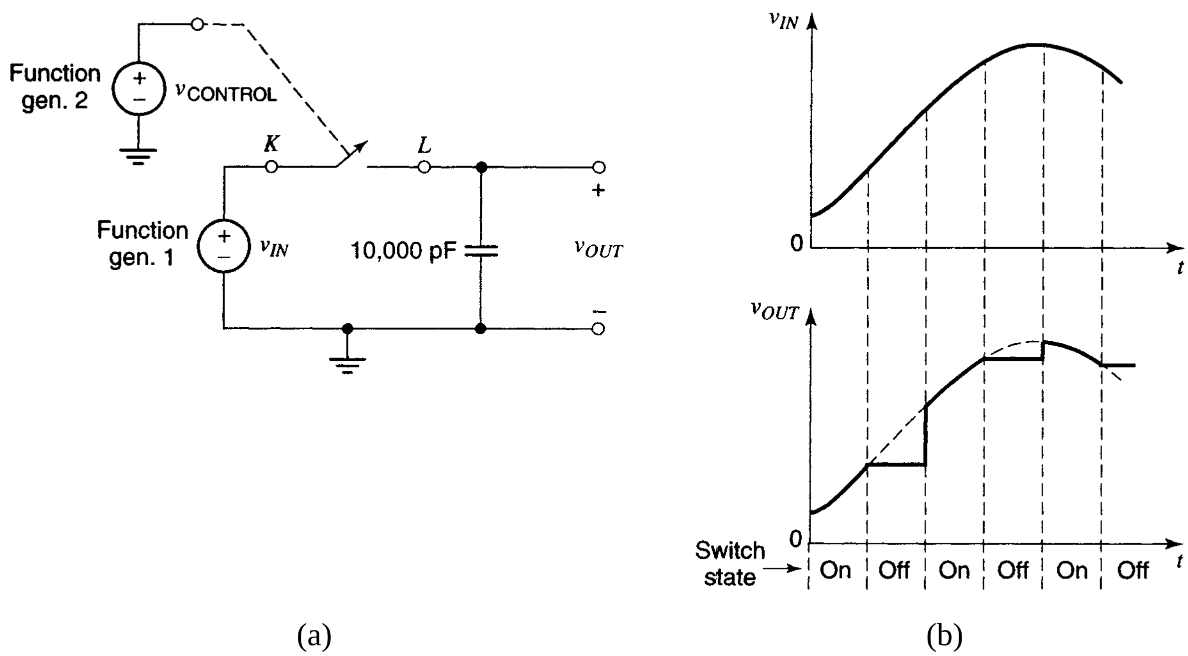


Figure 9

18. Assume that the input voltage is again a 1 kHz sinusoidal voltage with an amplitude of 1 V and that the control voltage is a 10 kHz square wave, taking values +2 V and -2 V. Without building the track-and-hold circuit, sketch the expected waveform at the output, based on the description of its operation in step 17.

19. Now build the circuit and try it. Use the scope as explained in step 16. Again, careful fine-tuning of the control voltage generator's frequency will be needed obtain a stable display. Is the output waveform. as you expected in step 18?

NOTE 1: If your input signal generator has difficulty in driving this circuit, insert a resistance of a few hundred ohms between the signal generator and point K. This will ease the load on the signal generator.

NOTE 2: The output waveform of the track-and-hold contains a varying part and a constant part for each cycle of the control voltage. The time duration of the varying part can be made short by making the duty cycle of the control voltage small (a duty cycle is the percentage of the control voltage period during which the square wave has a positive value).

A SAMPLE-AND-HOLD CIRCUIT (OPTIONAL)

20. If you still have time, you can ponder this question: Can you think of a way to further process the output signal of the circuit in Fig. 9(a), so that the varying part in each control voltage period is eliminated? You would need an additional track-and-hold circuit to do this. Do not build such a circuit; just explain how you would build it if you had to. Circuits that produce such waveforms at their output from a continuously varying input signal are called sample-and-hold circuits (or, more accurately, sample-delay-hold circuits). Sometimes, even the track-and-hold circuit is called a sample-and-hold circuit.