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QST Issue: Jan 2004
Title: Experiment #12--Field Effect Transistors
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Experiment #12—Field Effect Transistors

Welcome to the second year of "Hands-On Radio." After an introduction and 11 experiments, we've covered a lot of ground but it seems like we've only scratched the surface! Radio electronics is a pretty broad field, so there are lots of experiment topics remaining.

The field effect transistor, or FET, is an attractive replacement for bipolar transistors in switches and amplifiers. Why? The FET offers high input impedance, excellent gain, and easy biasing. We'll revisit the first "Hands-On Radio" experiment and find out how these characteristics fit the common-emitter design.

Terms to Learn

- *Transconductance*—The measure of change in output current caused by a change in input voltage.
- *Channel*—The semiconductor material between an FET drain and source through which current flows.
- *Enhancement and depletion mode*—In enhancement-mode FETs, increasing gate voltage causes channel conductivity to increase. For depletion-mode FETs, the opposite is true.
- *On-resistance*—The drain-to-source resistance of an FET's channel at maximum conductivity.

Background

While you may know that John Bardeen, Walter Brattain and William Shockley constructed the first bipolar transistor in 1948, you may not know that the idea behind the FET was patented in 1926 by Julius Lilienfield. A working (but very slow) amplifier was made using salt by Robert Pohl in 1938. The FET is actually the oldest transistor and its operation is much closer to the vacuum tube than the bipolar transistor.

Figure 1 shows the rudimentary construction and symbols for the two primary types of FETs, the junction FET (JFET) and the metal-oxide-semiconductor FET (MOSFET), that we met in experiment #9. Metal electrodes attach leads to the semiconductor material. The junction in a JFET is formed by the different material types (P and N) of the gate and the channel. MOS describes the construction of the gate; a metal electrode coating an insulating layer of oxide (usually quartz, silicon dioxide or SiO_2) which, in turn, contacts the channel material directly. FET and bipolar transistors have terminals with similar functions—gate and base, collector and drain, and emitter and source.

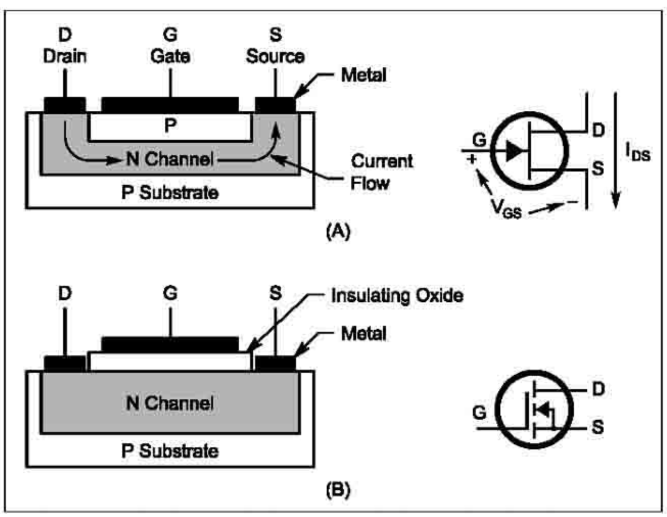

Figure 1—JFET (A) and MOSFET (B) construction are shown along with their symbols. N-channel, enhancement-mode devices are shown.

Where the bipolar transistor uses input current to control output current, the FET uses input voltage. In place of the bipolar transistor's pair of P-N junctions placed back-to-back between collector and emitter, the FET has a *channel* of either P-type or N-type material. In the bipolar transistor, current flows from the base to emitter, controlling current flow through the two P-N junctions. In the FET, gate voltage changes the conductivity of the channel and so the current flowing between drain and source also changes. Very little current flows in the gate of an FET.

Like the bipolar transistor's NPN and PNP devices, the FET comes in different flavors, but it has *four* instead of two. Figure 1 shows N-channel devices, but the channels can be made of either N or P-type material and the device can be designed so that increasing gate voltage causes more or less current to flow in the channel. If more channel current flows with increasing gate voltage, it is an *enhancement-mode* device. Conversely, *depletion-mode* devices have less current with increasing gate voltage. The most widely used device is the N-channel enhancement-mode FET.

The change in output current caused by a change in input voltage is called *transconductance*. Analogous to a bipolar transistor's current gain or beta, its symbol is g_m and its units are siemens (S) because it measures the ratio of current to voltage.[1] The input voltage, V_{GS}, is measured between the FET gate and source. The output current, I_{DS}, flows from drain to source.

$$g_m = \Delta I_{DS} / \Delta V_{GS} \text{ and } \Delta I_{DS} = g_m \Delta V_{GS} \qquad \text{[Eq 1]}$$

The voltage gain of the FET amplifier in Figure 2 depends on the FET transconductance because varying the current in the FET drain causes a varying voltage across the drain resistance. The model for the FET is the variable resistive divider shown in Figure 2A, with V_{GS} controlling the value of R_{DS}. If V_O is measured at the drain terminal (just as the common-emitter output voltage is measured at the collector), then

$$\Delta V_O = -\Delta I_{DS} R1 = -g_m \Delta V_{GS} R1 \qquad \text{[Eq 2]}$$

Substituting this relationship gives voltage gain in terms of transconductance and the drain load:

$$A_V = \Delta V_O / \Delta V_{GS} = -g_m R1 \qquad \text{[Eq 3]}$$

[1]Siemens (pronounced "see-mins") is the international unit for conductance, formerly mhos. Its symbol is a capital "S" and 1 siemens = 1 A/V.

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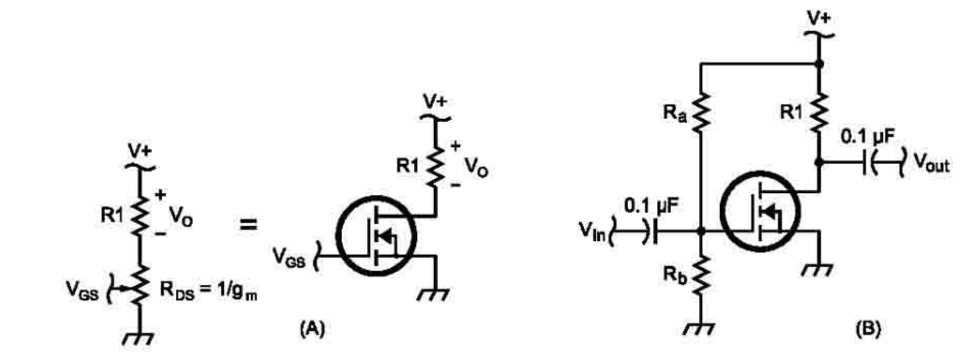

Figure 2—(A) A MOSFET common-source amplifier can be modeled as a variable voltage divider between the drain load and the FET. (B) A simple MOSFET amplifier with a voltage divider for supplying gate bias.

The minus sign results from the output voltage decreasing as drain current increases, just as with the common-emitter amplifier.

A key difference between the FET and bipolar transistor is that the channel of an FET acts like a variable resistance. That means that drain-to-source voltage can become quite low—lower than a completely saturated bipolar transistor's V_{CE}. Note that the *on-resistance* for power FETs can be very low—in the milliohm range. This allows them to switch heavy loads while dissipating little power. In amplifiers, this also allows more output voltage swing.

Another important parameter of FETs is the gate-to-source voltage at which no more current flows through the channel. This is called the *pinch-off voltage*, V_P. Imagine the gate voltage as a pair of fingers tightening or loosening around a hose carrying a stream of water and you'll have a pretty good idea of the mechanics involved. When V_{GS} reaches V_P, the area of the channel through which current flows is reduced to zero. Depending on the type of FET, V_P can be positive or negative. Switching MOSFETs are generally designed to have V_P greater than zero to make interfacing with digital logic easier. The voltage at which the MOSFET begins to conduct current is usually shown as $V_{GS(TH)}$, the *gate threshold voltage.*

Testing a MOSFET Common-Source Amplifier

This experiment will use a common switching MOSFET, the IRF510. This is a large transistor capable of handling several amps of drain current, but it demonstrates the mechanics of MOSFET amplifiers well. You may want to download the data sheet for the transistor.[2]

- When using a single power supply, it's necessary to bias the gate so that output voltage can both increase and decrease. Bias is supplied by R_a and R_b which act as a voltage divider—$V_{GS} = R_b / (R_a + R_b)$. For the divider, use a 10 kΩ potentiometer with the wiper connected to the FET gate and the remaining leads connected to V+ and ground. Start with the potentiometer set so that the wiper is nearly at ground voltage. Leave the input signal source disconnected.
- The IRF510 can handle a lot of current, but we'll limit drain current to 12 mA by using a 1 kΩ resistor for R1.
- Monitor the FET drain voltage and slowly adjust the bias pot so that gate voltage increases. When the gate threshold voltage is reached, the FET will start conducting and drain voltage will fall rapidly to zero. Record the gate threshold voltage as well as the voltage when the FET drain is 1 V below V+ and 1 V above ground.
- Set the signal generator to output a 0.1 $V_{p\text{-}p}$ 1 kHz sine wave. Set the bias voltage halfway between $V_{GS(TH)}$ and V+. Connect the input signal. Observe the output voltage and experiment by adjusting the bias voltage to get the largest undistorted output.
- Calculate voltage gain, $A_v = -$ (drain voltage change) / (gate voltage change) and transconductance, $g_m = -A_v / R1$. My FET showed a voltage gain of –18 and a transconductance of 0.018 S.
- Experiment by varying R1 and observing the effect on voltage gain. Readjust the bias setting and input voltage to get the maximum undistorted output voltage for each value of R1.

You may be asking yourself why your measured transconductance is so low compared to the specified minimum of 1.3 S in the data sheet. The answer lies in the graph of transconductance versus drain current (Figure 12 in the data sheet). The IRF510 transconductance is optimized for drain currents of several amperes and it falls off drastically at low currents.

Suggested Reading

Begin by reading the ARRL *Handbook* sections on FETs, beginning on pages 8.23 and 10.32. *The Art of Electronics* devotes all of Chapter 3 to FETs, with sections 3.07 and 3.08 covering amplifier design.

Shopping List

- IRF510 transistor (RadioShack 276-2072)
- 10 kΩ potentiometer (multi-turn preferred, but not required)
- Two 0.1 µF capacitors
- 1 kΩ, ¼ W resistor

Next Month

We have focused on active circuits throughout the first year of "Hands-On Radio." It's time to consider a passive circuit for a change. Next month, we'll explore several types of attenuators and their design equations.

The Hands-On Radio Web site is **www.arrl.org/tis/info/html/hands-on-radio/**.

[2]The IRF510 data sheet may be downloaded from **www.rigelcorp.com/__doc/8051/IRF510.pdf**. (Note: There are two consecutive underscores prior to "doc.")

FEEDBACK

◊ Experiment #12 of "Hands-On Radio" [Jan 2004, Figure 2, page 62], should show V_o with its "+" sign at the bottom of R1 and referenced to ground. This will then be consistent with Equation 2.—*tnx Jason Dugas, KB5URQ*