Field Effect Transistors and Noise

Purpose

In this experiment we introduce field effect transistors. We will measure the output characteristics of a FET, and then construct a common-source amplifier stage, analogous to the common-emitter bipolar amplifier we studied in Experiment 7. We will also learn to measure amplifier noise, and use our common-source amplifier to measure the thermal noise of a resistor.

Introduction

As we discussed in Experiment 7, transistors are the basic devices used to amplify electrical signals. They come in two general types, bipolar transistors and field effect transistors (FETs). The input to a FET is called the gate, analogous to the base of a bipolar transistor. But unlike the situation with bipolar transistors, almost no current flows into the gate, and FETs are nearly ideal voltage amplifiers with very high input impedance. In junction FETs (JFETs) the gate is connected to the rest of the device through a reverse biased pn junction, while in metal-oxide-semiconductor FETs (MOSFETs) the gate is connected via a thin insulating oxide layer. Bipolar transistors come in two polarities called npn and pnp, and similarly FETs come in two polarities called n-channel and p-channel.

In integrated circuit form, small MOSFETs are ubiquitous in digital electronics, used in everything from simple logic circuits to the 50-million transistor Pentium IV processor chip. Small MOSFETs are also used in some op-amps, particularly when very low supply current is needed, as in portable battery-powered circuits. Small discrete (single) MOSFETs are not normally used because they are extremely fragile. Large discrete MOSFETs are used in all sorts of high power applications, including commercial radio transmitters.

JFETs excel in the low-noise department, and a JFET input op-amp is often the first choice for low-noise amplification. Discrete JFETs are commonly seen in scientific instruments. In this experiment we will study an n-channel JFET (the 2N4416A) with excellent low-noise performance. Like bipolar transistors, JFETs suffer from wide “process spread”, meaning that critical parameters vary greatly from part to part. We will start by measuring the properties of a single device so that we can predict how it will behave in a circuit. Then we will build a common-source amplifier from our characterized JFET, and check its quiescent operating voltages and gain.

Noise is an important subject in electronics, especially for scientists who need to construct sensitive instruments to detect small signals. Some experiments are limited by external interference that is not intrinsic to the measuring instrument, but if that can be removed there will still be noise generated by the measuring electronics itself. The main sources of this noise are usually 1) the thermal noise of resistors, an unavoidable consequence of the equipartition theorem of statistical mechanics, and 2) noise from active components such as transistors. To introduce the subject of noise we will first measure the noise of the lock-in amplifiers we have in the lab. Next, we will reduce the effects of this noise by using our JFET common source amplifier as a low-noise pre-amplifier for the lock-in. Finally, we will use our JFET amplifier to measure the thermal noise of a resistor.

Readings

1. Sections 3.01-3.10 of H&H introduce FETs and analog FET circuits. You might find that this is more than you want or need to know about FETs. In that case, you could read instead Application Note AN101 "An Introduction to JFETs" from Vishay/Siliconix. There is a link to it on our course web site. You will also find on our web site the data sheet for the 2N4416A, the n-channel JFET we will be using.
2. Amplifier and resistor noise is discussed in H&H sections 7.11-7.22. Read at least Sections 7.11 and 7.12.
3. (Optional) If you are on campus you can read the original 1934 papers on resistor thermal noise by Johnson and Nyquist. See the links on our web site.

Theory

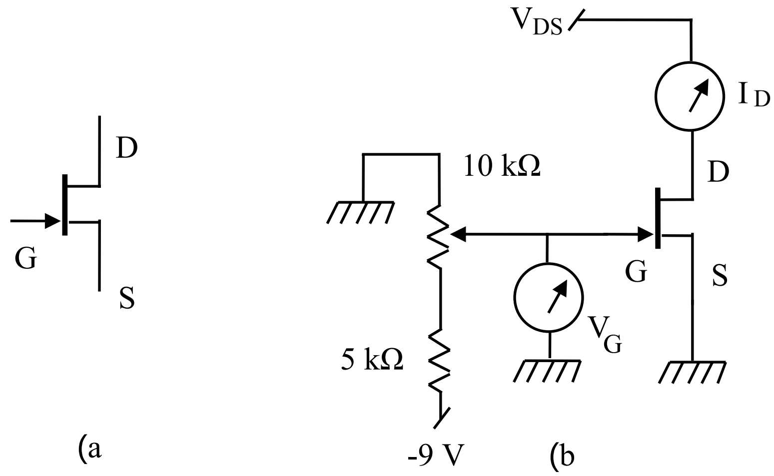

Figure 8.1 a) N-channel JFET b) Measuring Output Characteristics

JFET CHARACTERISTICS

The schematic symbol shown in Fig. 8.1a is used for the n-channel JFET. For the p-channel version the arrow points the other way and all polarities discussed below would be reversed. The three leads are gate (G), drain (D), and source (S). The path from drain to source through which the output current normally flows is called the channel. In many ways, the gate, drain and source are analogous to the base, collector and emitter of an npn transistor. However, in normal operation the gate voltage is always below the source voltage (this keeps the gate pn junction reverse biased) and almost no current flows out of the gate. The voltage of the gate relative to the source (V_{GS}) controls how much current flows from drain to source through the channel.

For more detail, look at the Output Characteristics graphs on page 7.3 of the 2N4416A data sheet. The drain-to-source current (I_D) is plotted versus the drain-to-source voltage (V_{DS}) for various values of the controlling gate voltage (V_{GS}). The JFET is normally operated with V_{DS} greater than about 3 V, in the "saturation region" where the curves have a small slope. In this region the current is nearly constant, independent of V_{DS}, but controlled by V_{GS}. Thus the JFET can be viewed as a voltage-controlled current source. The gain of a JFET is described by the transconductance g_{fs}:

$$g_{fs} \equiv \frac{\delta I_D}{\delta V_{GS}}$$

which tells us how much change in drain current results from a small change in the gate voltage. This quantity is called a conductance because it has the dimensions of inverse ohms, and a transconductance because the current and voltage are not at the same terminal. In the SI system one inverse ohm is called a Siemans (S). According to the data sheet, g_{fs} is guaranteed to be between 4.5 and 7.5 mS at V_{GS} =0 for V_{DS} =15V.

Like the β of a bipolar transistor, g_{fs} is not really a constant, and it has large process variations. The transconductance only varies a little with V_{DS} as long as V_{DS} is greater than about 3V. The dependence on V_{GS} is more rapid (see the plot on the data sheet). The transconductance is maximum at V_{GS} =0, where the best noise performance also occurs.

Other properties of the JFET also have large process variations. The saturation drain current I_{DSS} is the value of I_D at V_{GS} =0 and some large value of V_{DS}, usually 15 V. You can see that this quantity is about 7 and 11 mA for the two devices in the plots at the bottom of page 7.3 of the data sheet. According to the table on page 7-2, I_{DSS} is guaranteed to be between 5 and 15 mA, a very wide range for the designer to cope with. Another useful quantity is the gate-source cutoff voltage $V_{GS(off)}$, the value of V_{GS} where I_D drops to zero. For the two devices on page 7.3 this is -2 V and -3 V, but the data sheet only promises that it will be between -2.5V and -6V, again a very wide range.

Because of the wide variation of JFET parameters, a good starting point for any JFET circuit development is to plot your own output characteristic curves for the device at hand. There is an instrument called a <u>curve tracer</u> that can do this for you automatically, but in this lab we will let you do it once by hand, using the set-up shown in Fig. 8.1b. The drain is connected to a variable voltage source that controls V_{DS}, and there is a current meter (ideally with zero voltage drop across it) in series with the drain to measure I_D. You also need a (negative) variable voltage source between the gate and ground to set V_{GS}. Since the gate has very high impedance it is sufficient to use a potentiometer. Finally, a voltmeter between the gate and ground is used to measure V_{GS}.

COMMON SOURCE AMPLIFIER

A JFET common-source amplifier stage is shown in Fig. 8.2. To keep things simple we are supposing that the input signal has a dc value of 0 V, so the desired quiescent gate voltage (V_{GS}=0) is achieved without the need for a dc blocking capacitor and a voltage divider like we used for our bipolar common-emitter amplifier. A small change in the input voltage δV_{in} causes a change in the drain current equal to $g_{fs} \cdot \delta V_{in}$, and this current dropped across the drain resistor R_D causes an output voltage $\delta V_{out} = -R_D \cdot g_{fs} \cdot \delta V_{in}$. Thus, the voltage gain of this stage is simply $G = -R_D \cdot g_{fs}$. For typical values of R_D and g_{fs} the gain of a single JFET common-source stage is in the range 5-20, much less than the maximum gain possible with a bipolar common emitter stage.

Both the gain of this stage and the quiescent voltages suffer from wide process variations. These variations can be reduced by adding a resistor to the source like we did for the bipolar version, and sometimes this is done in practice, but not always because the gain will then be even smaller. Process variations of gain due to variations of g_{fs} are often dealt with in practical circuits by including the stage in a feedback loop. Then variations of g_{fs} cause variations in the loop gain, but not in the closed loop gain. For more about JFET biasing and the effects of process variations, see Application Note AN102 "JFET Biasing Techniques" from Vishay/Siliconix (linked at our course web site).

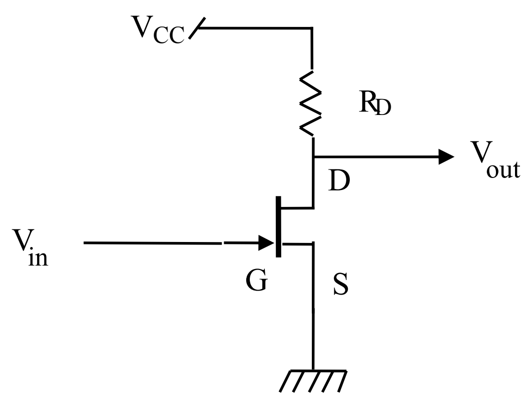

Figure 8.2 Common Source Amplifier Stage

The input resistance of this stage is essentially infinite (something like 10^{12} Ω) and the input capacitance is around 10 pF. The output impedance is equal to the drain resistance R_D, typically a few thousand ohms. Compared to the bipolar version, the JFET common-source stage has much higher input impedance, lower gain, and comparable output impedance. We did not discuss the noise of the bipolar common-emitter stage, but its worth knowing that the JFET common-source stage has much lower noise when the signal source impedance is above about 10 kΩ.

RESISTOR THERMAL NOISE

Every resistor in thermal equilibrium has a fluctuating voltage across it called Johnson noise. This noise is an unavoidable consequence of the equipartition theorem of statistical mechanics. (See any text on statistical mechanics for a discussion, or read the original papers by Johnson (the experimenter) and Nyquist (the theorist), linked on our web site.) A circuit model for a noisy resistor is shown in Fig. 8.3.

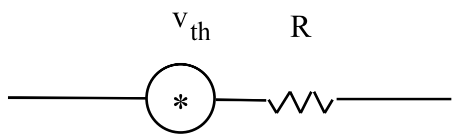

Figure 8.3   Noisy Resistor

The little circle with a star inside is a voltage source, but instead of generating a sine wave or a dc voltage, it generates a mean-zero gaussian distributed random waveform, otherwise known as noise. You might think we could describe this noise source by its standard deviation or rms voltage, but that is not a well-defined quantity until we pass the noise waveform through a band-pass filter that gives us well-defined bandwidth. This is because the noise waveform fluctuates at all frequencies (that is, if we ignore quantum freeze-out at very high frequencies), but any time we observe it we will do so with finite bandwidth. The rms voltage we read will increase as the bandwidth increases, since we see more and more of the generated fluctuations. The mean-square fluctuations (called the "noise power") increase in proportion to the bandwidth, the absolute temperature T, and the resistance R, so the rms fluctuations must increase as the square root of these quantities. Nyquist derived the famous formula:

$$v_{th} = \sqrt{4kTR}$$

where k is Boltzmann's constant. (If you have already learned about the black-body spectrum, then you know about a more complex example of the same thing. One can show that the Nyquist formula is equivalent to the black body formula in one dimension.) The most common units of v_{th} are $\text{nV}/\sqrt{\text{Hz}}$ (nano-volts per root hertz). To find the rms noise, you multiply v_{th} by the square root of the bandwidth you use to observe it. You can avoid having to plug numbers into Nyquist's formula if you can remember that a 60Ω resistor at 300 K generates $1\,\text{nV}/\sqrt{\text{Hz}}$ of Johnson noise.

Noise quantities with units like v_{th} are called noise spectra, while the squares of these quantities are called power spectral densities. Most noise spectra depend on frequency, but thermal noise does not. By analogy to visible light we say that thermal noise has a white spectrum.

You can handle voltage noise sources in circuit calculations just like you would any other voltage source. However, if there are several noise sources (say v_1 and v_2) contributing to the fluctuating voltage at some point in the circuit you find the total noise spectrum v_3 by adding the contributions "in quadrature":

$$v_3 = \sqrt{(v_1)^2 + (v_2)^2} \quad \text{or} \quad v_3 = v_1 \oplus v_2$$

The second form is just a shorthand for the first expression.

AMPLIFIER NOISE

Figure 8.4 shows a circuit model for an ideal voltage amplifier with noise sources. The triangle represents a noise-less voltage amplifier with gain G and infinite input impedance. All of the effects of the amplifier's noise are represented by a voltage noise source with noise spectrum v_n and a current noise source with noise spectrum i_n. The units for amplifier voltage and current noise are usually $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and $\mathrm{fA}/\sqrt{\mathrm{Hz}}$ (femto-amps per root hertz).

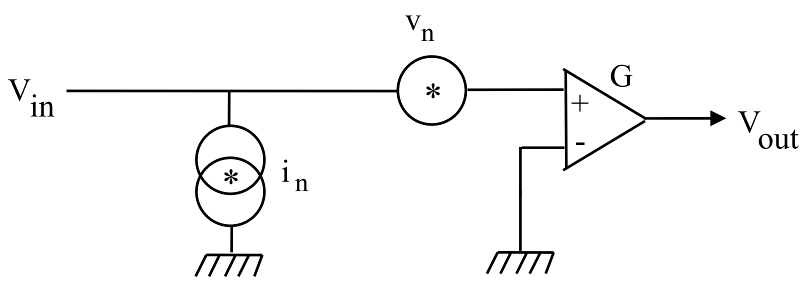

Figure 8.4   Noisy Voltage Amplifier

Suppose we connect a resistor R with thermal noise v_{th} between ground and the input of this amplifier. The total noise spectrum at the output will be:

$$v_{out} = G \cdot \left(v_{th} \oplus v_n \oplus i_n R \right)$$

The first term is the resistor thermal noise, which is an input signal from the amplifier's point of view. The second term is the amplifier voltage noise, and the third is the effect of the current noise, which generates a voltage by driving current through the resistance R. All three terms are added in quadrature (square root of the sum of the squares) and then multiplied by the amplifier gain G. A complete model for the noise properties of an amplifier always requires both a voltage noise source and a current noise source. The voltage noise source represents the noise present when the amplifier input is shorted (R=0) while the current noise source represents noise currents that flow in the input circuit and drive the impedance connected to the input.

Problems

1. Consider the common-source amplifier circuit of Fig. 8.2. Suppose you build this circuit with the JFET used to generate the output characteristics shown in the 2N4416A data sheet, lower right plot on page 7.3. If we use V_{CC} = 9 V, and we want V_{DS} =3 V at V_{GS} =0, what value of R_D should we use? What will the value of I_D be? What value of R_D should we use if V_{CC} is 18V, and what will I_D be in this case?

2. Find the small-signal voltage gain of the common-source stage you designed in Problem 1, for both values of V_{CC}. Estimate any quantities you need from the lower right plot on page 7.3 of the data sheet (do not use typical values given in the tables).

3. Suppose you measure the Johnson noise of a 5 kΩ resistor, observing the fluctuations through a 1 Hz bandwidth filter centered at 2 kHz. What rms voltage will you observe (expressed in nV)? How about if the filter bandwidth is 10 Hz? Assume the temperature is 300 K.

4. Suppose we have a 5 kΩ and a 3 kΩ resistor in series. Compute the total Johnson noise by adding in quadrature the noise of the two resistors. Give an answer for the total noise in units of $\mathrm{nV}/\sqrt{\mathrm{Hz}}$. Now consider a single 8 kΩ resistor and find its thermal noise. Do you get the same answer? Again assume the temperature is 300 K.

Experiment

JFET OUTPUT CHARACTERISTICS

Use the same 2N4416A JFET for all of your experiments this week. Find the pin-out diagram on the data sheet, and build the circuit shown in Fig. 8.1b. (The lead marked C on the pin-out diagram is connected to the case.) You can use the Tektronix power supply for the variable 0 to +15V drain voltage source. Make the gate voltage source from a 9V battery and a 10 kΩ 10-turn potentiometer. There are battery clips in the lab for use with the 9V batteries. You could use your DVM to measure the drain current, and one channel of the scope to measure the gate voltage. Check that the voltage drop across your DVM (ideally zero when measuring current) is small enough to be neglected, or if not measure the actual voltage at the JFET drain. Get enough data to sketch output characteristics similar to those shown in the data sheet for $V_{GS} = 0$, $V_{GS} = -0.1$ V, and one other value of V_{GS}. Vary V_{DS} from 0 to + 15V.

Measure the values of $V_{GS(off)}$ and I_{DSS} for your device. Find g_{fs} for your device at $V_{GS} = 0$ and $V_{DS} = +3V, +15V$. Does your device meet the specs given on page 7.2 of the data sheet? Check $V_{GS(off)}$, I_{DSS}, and g_{fs}.

COMMON-SOURCE AMPLIFER

Construct the common-source amplifier shown in Fig. 8.2. Use a 9V battery for the drain voltage source. First, measure the battery voltage. Then, compute, using your characteristic curves, the value of R_D that will give $V_{DS} = +3V$ at $V_{GS} = 0$, and also predict the small-signal voltage gain. If your predicted gain is less than 5, increase your power supply voltage by using two 9 V batteries in series and compute R_D and the gain again. Find a metal-film resistor close to your desired value of R_D (or use several in series) and measure the resulting quiescent voltage V_{DS} with the gate grounded. Is the value of V_{DS} you observe consistent with your measured characteristics?

Measure the small-signal gain of your common-source stage at 1 kHz. Do you get the value you predicted? If your measured gain is too small, consider the effects of the output resistance R_O of the JFET, which is the inverse of the slope of the I_D versus V_{DS} curve at the operating point. The simple gain formula we have been using ($G = -R_D \cdot g_{fs}$) is only exact in the limit $R_O >> R_D$. To avoid making this approximation, replace R_D in the gain formula with the parallel combination of R_D and R_O.

NOISE OF THE LOCK-IN AND COMMON SOURCE AMPLIFIER

Our goal in this section will be to measure the thermal noise of a 5 kΩ resistor. The lock-in alone does not have low enough noise to do the job, but we will be able to do it by using our JFET amplifier together with the lock-in.

The SR510 lock-in has circuitry that can measure the rms fluctuations at its output, divide this by the gain, and display the result as the equivalent rms voltage fluctuations at the input. The bandwidth of this noise measurement (called the 'equivalent noise bandwidth' or ENBW) is determined by output filtering built into the lock-in, and it can be set to either 1 Hz or 10 Hz. The center frequency is determined by the frequency of the reference applied to the lock-in. First we will measure the noise of the lock-in amplifier with its input shorted. Set up the lock-in as follows:

SIGNAL INPUTS: A	BANDPASS: IN	LINE: IN	LINEx2: IN
SENS.: 100 nV full scale	DYN. RES.: MED	DISPLAY: NOISE	
EXPAND: x1	REL.: OFF	ENBW: 10 Hz	

Connect 'minigrabber' test leads to the lock-in A input using a BNC male-to-male adaptor, and connect the two clips together so the lock-in input is shorted. Set your signal generator to 1050 Hz and connect the SYNC output signal to the lock-in reference input. You should see the lock-in 'unlock' light go out. We use 1050 Hz to avoid interference from the 60 Hz harmonics likely to be present at 1020 Hz and 1080 Hz.

If at any point below you find that the lock-in is overloading, try raising the sensitivity setting.

Record the noise measured by the lock-in in nV rms. Convert this value to $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ using the measurement bandwidth. Is the lock-in noise small compared to the thermal noise of a 5 kΩ resistor?

You will notice that the result displayed by the lock-in fluctuates with time. This is unavoidable when measuring a statistical quantity (like the rms of noise) with a finite amount of data. You can reduce the uncertainly in your measurement by averaging 10 readings of the display. Be sure to make your measurements at definite times (like once every 10 seconds) so that you don't unconsciously select data to get a result you want.

(A detail: if you connect 5 kΩ to the lock-in input you will have a contribution from the lock-in current noise i_n as well as from its voltage noise. We have only measured the voltage noise v_n.

However, with R=5 kΩ the contribution of the current noise $i_n \cdot R$ is small compared to the voltage noise v_n.)

To reduce the input noise of your measurement system, we will use your JFET amplifier as a pre-amplifier for the lock-in. Connect the output of your JFET stage to the lock-in using the 'minigrabbers' (use the shortest possible leads to help reduce interference). Now short the gate of your JFET directly to the source using a short wire. (There should be no grounds connected to your JFET stage other than the connection to the ground side of the lock-input.) Record the rms noise measured by the lock-in in this configuration. To find the input voltage noise v_n of the lock-in/JFET amplifier combination, you have to divide the displayed rms voltage by the square root of the measurement bandwidth and by the gain of your JFET common source stage. The result you obtain should be equal to the input voltage noise of a 2N4416A (about 3 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 1 kHz), plus small contributions from other sources. Is the amplifier noise now small compared to the thermal noise of a 5 kΩ resistor?

(Some more details: Because noise sources add in quadrature the amplifier noise does not have to be much smaller than the resistor noise. If the amplifier noise is 30% of the resistor noise it only makes a 4% contribution to the quadrature sum. Again, we have only measured v_n, not both v_n and i_n. But the JFET current noise i_n is very small, about 1 $\mathrm{fA}/\sqrt{\mathrm{Hz}}$, so the current noise contribution $i_n \cdot R$ to the total noise at the input is only 5 $\mathrm{pV}/\sqrt{\mathrm{Hz}}$ for R=5 kΩ. The lock-in input noise is still present, but it now has a much smaller effect because it is divided by the gain of the JFET stage.)

THERMAL NOISE OF A RESISTOR

Connect a 5 kΩ resistor between the gate and source of your JFET. Connect it directly from gate to source and trim the resistor's leads to reduce your sensitivity to interference. Measure the total noise at the input in $\mathrm{nV}/\sqrt{\mathrm{Hz}}$. Does the measured thermal noise of the resistor agree with Nyquist's formula? If it makes a significant difference (within the uncertainties of your measurement), you can subtract off (in quadrature) the amplifier noise contribution to the total noise to obtain the resistor noise alone.

Since the Nyquist formula is a result of statistical mechanics, it is as reliable as any physical theory can be. Therefore, if you trust your measurement, you can turn things around and use the measured resistor thermal noise and the Nyquist formula to measure the absolute temperature of the resistor. You have made a noise thermometer.

COMMENTS ON NOISE MEASUREMENTS

In this experiment we have 'walked you through' a noise measurement, being careful to avoid a number of pitfalls that can cause plenty of trouble for the unwary. Making noise measurements and debugging circuits that are supposed to be low-noise but aren't can be a tricky business. Almost every part is a potential source of noise and every noise signal looks pretty much the same, so it is not easy to tell where extra noise is coming from. Here are some things to consider if you get more deeply involved in electronic noise:

1) Get a spectrum analyzer (H&H 15.18) and use it to measure noise instead of a lock-in. A spectrum analyzer displays the full frequency dependence of the noise spectrum, instead of the value at one frequency at a time. It gives you a chance to distinguish different noise sources and helps to avoid confusion from interference.

2) Most power supplies are noisy, and they often involve ground connections that you would be better off without. Rechargeable lead-acid gel batteries are good low-noise power supplies. For safety be sure to use a fuse on any battery larger than about 1 A-hr capacity.

3) Use metal shielded test enclosures. We got away without shielding in this experiment because we had a low-impedance input circuit and short leads.

4) All passive components generate thermal noise, not just resistors. Remember that little resistor r used to represent the loss in the inductor we made in Experiment 3? It generates thermal noise, and so do the losses in capacitors.

5) A resistor with a bias current flowing through it is not in thermal equilibrium, so it is allowed to generate more than just the Nyquist thermal noise. In fact, carbon resistors can be pretty bad (see H&H Section 7.11). To preserve your sanity, use only metal-film resistors in low-noise circuits (1% resistors are usually metal-film).