Experiment #9—Designing Drivers

Transistors make great switches as well as amplifiers. In fact, computers are built of millions of transistors acting as switches. Any circuit that controls or supplies power to a heavy load is called a *driver*. In this experiment we will learn how to make a transistor switch that can turn a heavy load on and off reliably. (Thanks to George, KF6VSG, for suggesting the topic.)

Terms to Learn

- *Cutoff*—the point at which collector current reaches zero
- *Linear Region*—when a transistor is operating between cutoff and saturation, it is in its linear region.
- *Saturation*—the point at which increases in base current do not cause a further increase in collector current
- *Transconductance*—the change in output current in response to a change in input voltage

The Transistor as a Switch

The goal when designing amplifiers is to make the transistor's collector current linearly and faithfully follow (proportionally) its base current. This requires that the transistor stay within its *linear region*—conducting some current at all times. A switch has completely different properties—its output current is either zero or some maximum value. Figure 1 shows both a bipolar and metal-oxide semiconductor field-effect transistor (or MOSFET) switch circuit. You'll notice that there are no bias resistors in either circuit.

Before we proceed, a primer on the MOSFET—just "FET" from here on—is in order. The FET drain corresponds to the bipolar collector, the gate to the base and the source to the emitter. The FET's drain-to-source current, I_{DS}, is controlled by the gate-to-source voltage, V_{GS}.

Similar to the NPN or PNP bipolar transistor, the FET comes in N-channel and P-channel flavors. (The arrowhead points into the symbol for N-channel devices.) Unlike the bipolar transistor, the FET has both depletion and enhancement modes. An enhancement mode device is similar to a bipolar transistor—it does not conduct without an input signal. In an enhancement-mode FET, as V_{GS} increases, so does I_{DS}. The depletion mode acts just the opposite. The FET symbol in Figure 1 is of an N-channel, enhancement mode device.

When a bipolar transistor's collector current reaches zero, the transistor is said to be in cutoff. As base current increases, so will collector current until the transistor reaches saturation. In saturation, collector current can't increase any further, even if base current is increased, and V_{CE} is at its minimum value. The analogous states in a FET are called *fully on* and *fully off*. The voltage and current waveforms below the circuit show how the load current reacts to V_{IN}.

Since the FET uses voltage to control its drain current, forward transconductance, g_{fs} measures the effect of the control signal.

$$g_{fs} = \Delta I_D / \Delta V_{GS} \qquad [1]$$

This parameter has the same units (Siemens, S) as conductance, which is the reciprocal of resistance (1/R). One can think of the FET acting as a voltage-controlled resistor, with g_{fs} showing how much the resistance value changes in response to changes in the gate voltage.

Designing Driver Circuits

First, select a transistor that can handle the load current and dissipate whatever power is lost as heat. Second, be sure that the input signal source can supply an adequate input signal (drive). You must meet both of these conditions to ensure reliable driver operation.

To choose the proper transistor, the load current and supply voltage must both be known. The supply voltage often varies widely. For example, a car's 12 V dc power bus may vary from 9 to 18 V dc, depending on battery condition and the state of the vehicle's charging system. The transistor must withstand the maximum supply voltage, V_{MAX}, when it is off.

The load resistance, R_L, must also be known. The maximum current the switch must handle is:

$$I_{MAX} = V_{MAX} / R_L \qquad [2]$$

Beware of surge currents at turn-on. Loads with capacitors may temporarily act like short circuits at turn-on. Also beware of voltage transients or "spikes" during switching. Inductive loads will present high voltages during the switch period (Remember that, for an inductor, V = L di/dt—the faster we try to change current through it, the higher the voltage). Your driver will therefore have to handle any current surges or voltage spikes induced by the load. ("Snubber" circuits, consisting of a clamp diode and a resistor-capacitor network, are frequently used to protect the driver from the spikes of inductive loads.) If you are using a bipolar transistor, you now can calculate how much base current you must supply to the switch:

$$I_B = I_{MAX} / \beta$$

β changes with collector current (it usually decreases as I_C increases), so use a value for β with I_C near I_{MAX}. This is specified on the transistor's data sheet. Using the *minimum* value for the input voltage, calculate the value of R_B:

$$R_B = (V_{INmin} - V_{BE}) / I_B \qquad [3]$$

The minimum value of input voltage must be used to accommodate the *worst-case* combination of circuit voltages and currents.

Designing with an FET is a little easier because the manufacturer usually specifies what the value of V_{GS} must be for the transistor to be fully on. The FET's gate, being insulated from the conducting channel, acts like a small capacitor of a few hundred pF and draws very little dc current. R_G in Figure 1 is required if the input voltage source does not actually output 0 V when off, such as a switch connected to a positive voltage. The FET won't turn off reliably if its gate is allowed to "float." R_G pulls the gate voltage to zero if the input is open-circuited. The input source must be able to supply current of V_{GS}/R_G.

Power dissipation is the next design hurdle. Even if the transistors are turned completely on, they will still dissipate some heat. Just as for a resistor, the switch power dissipation is:

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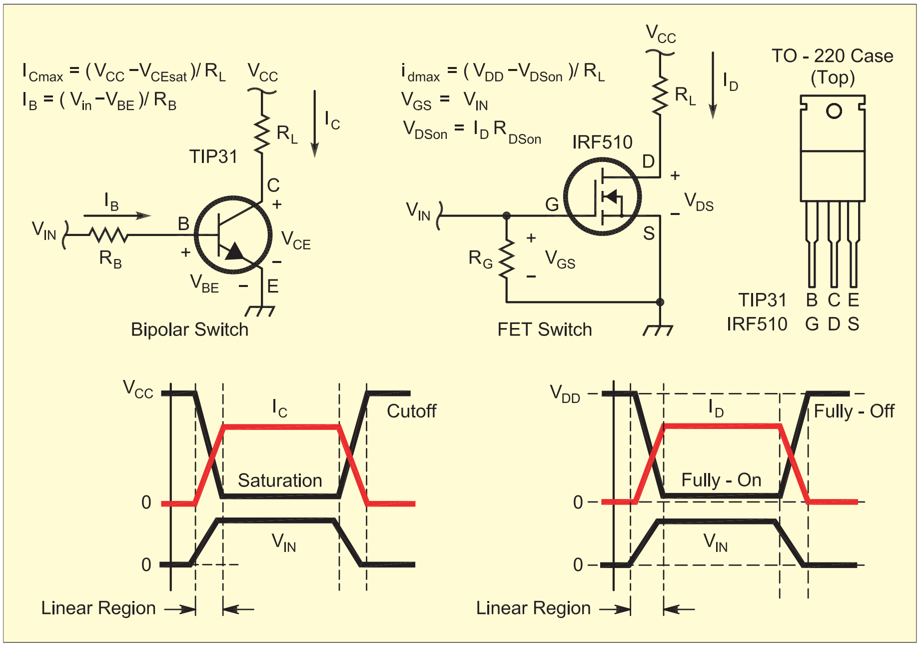

Figure 1—A pair of transistor driver circuits using a bipolar transistor and a MOSFET. The input and output signals show the linear, cutoff and saturation regions. The basing diagram for the TO-220 package is to the right.

Table 1
Comparison of Bipolar and MOSFET Power Transistors

Transistor Parameter (Typical Values)	*TIP 31*	*IRF510*
V_{CEsat}	1.2 V	N/A
R_{DSon}	N/A	0.4 Ω
V_{BE} or V_{GSon}	1.8 V	10 V
I_C or I_D	3.0 A	3.0 A
β or g_{fs}	25@I_C = 1 A	2 S (A/V)
P_{Dmax}	40 W	20 W

$P_D = V_{CE} I_C = V_{CEsat} I_{MAX}$ (for a bipolar transistor) [4]

and

$P_D = V_{DS} I_D = R_{DSon} I_{MAX}^2$ (for a FET) [5]

R_{DSon} is the resistance of the channel from drain to source when the FET is on. Modern FETs have a very low on-resistance, but still dissipate power when driving a heavy load. Some FETs have gotten so good, however, that their on-resistance is now below 2 milliohms (that's 0.002 Ω!). To put this in perspective, some modern power MOSFETs can handle 20 A of current, dissipate less than 1 W and not require a heat sink under moderate ambient conditions! Look at the transistor's data sheet for the manufacturer's R_{DSon} specification.

Power dissipation is why a switching transistor needs to be kept out of its linear region. When it's turned off or fully on, either the current through the transistor or the voltage across it is low, thus keeping the product of voltage and current (dissipated power) low. As the waveforms in Figure 1 show, while in the linear region, both voltage and current have significant values and the transistor is generating heat. It's important to make the transition through the linear region quick enough to keep the transistor cool.

Once you have calculated the power dissipation the switch must handle, you must check to see whether the transistor can withstand it. The manufacturer of the transistor will specify a *free-air dissipation* that assumes no heat-sink and room-temperature (ambient) air circulating freely around the transistor. This should be at least 50 percent higher than your calculated power dissipation. If not, you must either use a larger transistor or provide a heat sink. Let's make a driver!

Testing a Driver Circuit

- We're going to use a 25 Ω power resistor as a 0.5 A load, much like a heavy-duty solenoid or a small motor. Bipolar and MOSFET drivers will use a 12 V input signal. Table 1 shows the typical rating for two popular transistors.
- Solder the two 50 Ω resistors in parallel to create the load. Don't use your prototype board for this experiment due to the large currents—temporarily solder components together by their leads or use a terminal strip. The power supply should be able to deliver 12 V at 1 A.
- For the TIP31, if the collector current is to be 0.5 A and β is 25, base current must be at least 0.5/25 = 20 mA. From equation 3, the value of R_B = (12 – 1.8)/0.02 = 510 Ω.
- For the IRF510, since 10 V of gate drive is needed, the 12 V input signal can be used directly. Use a 4.7 kΩ resistor for R_G.
- Use equations 4 and 5 to calculate power dissipation for each transistor:
  TIP31: $P_D = 1.2 \times 0.5 = 0.6$ W
  IRF510: $P_D = 0.6 \times (0.5)^2 = 0.15$ W
  Load: $P_D = 25 \times (0.5)^2 = 6$ W — it will get warm, so keep it in the clear!
- Power up the circuit and use your voltmeter to check all of the transistor voltages. Load current can be calculated by measuring the voltage across the load and using Ohm's Law.
- Vary the amount of input current (TIP31) or voltage (IRF510) and observe the effect on the transistor's ability to drive the load. The base current can be varied by changing the value of R_B. The gate voltage can be varied by using a 20 kΩ potentiometer in series with R_G as a voltage divider.
- Place the transistor in its linear region for a short period by reducing the input signal and see how hot it gets—careful! You'll see why it's important to supply adequate drive.

Suggested Reading

Chapter 8 of *The 2004 ARRL Handbook* discusses both bipolar and MOSFET transistor construction. Chapter 3 of *The Art of Electronics*, by Horowitz and Hill, has a good section on power MOSFET switches and Chapter 6 reviews heat sinking. A list of Web links with technical tutorial information can be found on the Hands-On Radio Web site: **www.arrl.org/tis/info/html/hands-on-radio/**.

Shopping List

- TIP31 bipolar power transistor (RadioShack 276-2017), IRF510 MOSFET (RadioShack 276-2072)
- 1 package (2) of 50 Ω, 10 W resistors (RadioShack 271-133)
- 510 Ω, 4.7 kΩ 1/4 W resistors
- 20 kΩ potentiometer

Next Month

As long as we're experimenting with power control, this would be a good opportunity to explore the SCR—a thyristor that acts like a switch and is widely used for ac power control and switching.