TRANSISTORS

CHAPTER 2

INTRODUCTION

The transistor is our most important example of an "active" component, a device that can amplify, producing an output signal with more power in it than the input signal. The additional power comes from an external source of power (the power supply, to be exact). Note that voltage amplification isn't what matters, since, for example, a step-up transformer, a "passive" component just like a resistor or capacitor, has voltage gain but no power gain. Devices with power gain are distinguishable by their ability to make oscillators, by feeding some output signal back into the input.

It is interesting to note that the property of power amplification seemed very important to the inventors of the transistor. Almost the first thing they did to convince themselves that they had really invented something was to power a loudspeaker from a transistor, observing that the output signal sounded louder than the input signal.

The transistor is the essential ingredient of every electronic circuit, from the simplest amplifier or oscillator to the most elaborate digital computer. Integrated circuits (ICs), which have largely replaced circuits constructed from discrete transistors, are themselves merely arrays of transistors and other components built from a single chip of semiconductor material.

A good understanding of transistors is very important, even if most of your circuits are made from ICs, because you need to understand the input and output properties of the IC in order to connect it to the rest of your circuit and to the outside world. In addition, the transistor is the single most powerful resource for interfacing, whether between ICs and other circuitry or between one subcircuit and another. Finally, there are frequent (some might say too frequent) situations where the right IC just doesn't exist, and you have to rely on discrete transistor circuitry to do the job. As you will see, transistors have an excitement all their own. Learning how they work can be great fun.

Our treatment of transistors is going to be quite different from that of many other books. It is common practice to use the h-parameter model and equivalent circuit. In our opinion that is unnecessarily complicated and unintuitive. Not only does circuit behavior tend to be revealed to you as something that drops out of elaborate equations, rather than deriving from a clear understanding in your own mind as to how the circuit functions; you also have the tendency to lose sight of which parameters of transistor behavior you can count on and, more important, which ones can vary over large ranges.

In this chapter we will build up instead a very simple introductory transistor model and immediately work out some circuits with it. Soon its limitations will become apparent; then we will expand the model to include the respected Ebers-Moll conventions. With the Ebers-Moll equations and a simple 3-terminal model, you will have a good understanding of transistors; you won't need to do a lot of calculations, and your designs will be first-rate. In particular, they will be largely independent of the poorly controlled transistor parameters such as current gain.

Some important engineering notation should be mentioned. Voltage at a transistor terminal (relative to ground) is indicated by a single subscript (C, B, or E): V_C is the collector voltage, for instance. Voltage between two terminals is indicated by a double subscript: V_{BE} is the base-to-emitter voltage drop, for instance. If the same letter is repeated, that means a power-supply voltage: V_{CC} is the (positive) power-supply voltage associated with the collector, and V_{EE} is the (negative) supply voltage associated with the emitter.

2.01 First transistor model: current amplifier

Let's begin. A transistor is a 3-terminal device (Fig. 2.1) available in 2 flavors (*npn* and *pnp*), with properties that meet the following rules for *npn* transistors (for *pnp* simply reverse all polarities):

1. The collector must be more positive than the emitter.

2. The base-emitter and base-collector circuits behave like diodes (Fig. 2.2). Normally the base-emitter diode is conducting and the base-collector diode is reverse-biased, i.e., the applied voltage is in the opposite direction to easy current flow.

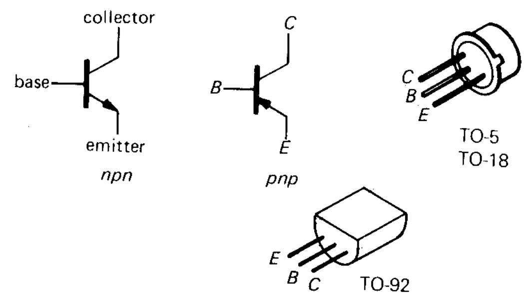

Figure 2.1. Transistor symbols, and small transistor packages.

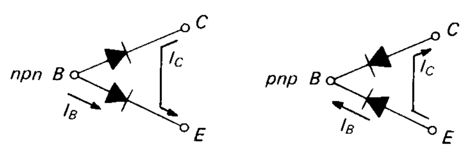

Figure 2.2. An ohmmeter's view of a transistor's terminals.

3. Any given transistor has maximum values of I_C, I_B, and V_{CE} that cannot be exceeded without costing the exceeder the price of a new transistor (for typical values, see Table 2.1). There are also other limits, such as power dissipation ($I_C V_{CE}$), temperature, V_{BE}, etc., that you must keep in mind.

4. When rules 1–3 are obeyed, I_C is roughly proportional to I_B and can be written as

$$I_C = h_{FE} I_B = \beta I_B$$

where h_{FE}, the current gain (also called beta), is typically about 100. Both I_C and I_E flow to the emitter. Note: The collector current is not due to forward conduction of the base-collector diode;

that diode is reverse-biased. Just think of it as "transistor action."

Property 4 gives the transistor its usefulness: A small current flowing into the base controls a much larger current flowing into the collector.

Warning: h_{FE} is not a "good" transistor parameter; for instance, its value can vary from 50 to 250 for different specimens of a given transistor type. It also depends upon the collector current, collector-to-emitter voltage, and temperature. *A circuit that depends on a particular value for h_{FE} is a bad circuit.*

Note particularly the effect of property 2. This means you can't go sticking a voltage across the base-emitter terminals, because an enormous current will flow if the base is more positive than the emitter by more than about 0.6 to 0.8 volt (forward diode drop). This rule also implies that an operating transistor has $V_B \approx V_E + 0.6$ volt ($V_B = V_E + V_{BE}$). Again, polarities are normally given for *npn* transistors; reverse them for *pnp*.

Let us emphasize again that you should not try to think of the collector current as diode conduction. It isn't, because the collector-base diode normally has voltages applied across it in the reverse direction. Furthermore, collector current varies very little with collector voltage (it behaves like a not-too-great current source), unlike forward diode conduction, where the current rises very rapidly with applied voltage.

SOME BASIC TRANSISTOR CIRCUITS

2.02 Transistor switch

Look at the circuit in Figure 2.3. This application, in which a small control current enables a much larger current to flow in another circuit, is called a transistor switch. From the preceding rules it is easy to understand. When the mechanical switch is open, there is no base current. So, from rule 4, there is no collector current. The lamp is off.

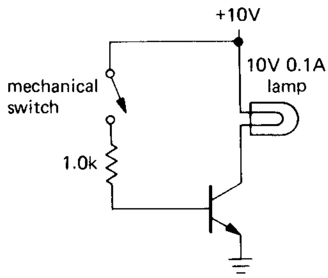

Figure 2.3. Transistor switch example.

When the switch is closed, the base rises to 0.6 volt (base-emitter diode is in forward conduction). The drop across the base resistor is 9.4 volts, so the base current is 9.4mA. Blind application of rule 4 gives $I_C = 940\text{mA}$ (for a typical beta of 100). That is wrong. Why? Because rule 4 holds only if rule 1 is obeyed; at a collector current of 100mA the lamp has 10 volts across it. To get a higher current you would have to pull the collector below ground. A transistor can't do this, and the result is what's called saturation – the collector goes as close to ground as it can (typical saturation voltages are about 0.05–0.2V, see Appendix G) and stays there. In this case, the lamp goes on, with its rated 10 volts across it.

Overdriving the base (we used 9.4mA when 1.0mA would have barely sufficed) makes the circuit conservative; in this particular case it is a good idea, since a lamp draws more current when cold (the resistance of a lamp when cold is 5 to 10 times lower than its resistance at operating current). Also transistor beta drops at low collector-to-base voltages, so some extra base current is necessary to bring a transistor into full saturation (see Appendix G). Incidentally, in a real circuit you would probably put a resistor from base to ground (perhaps 10k in this case) to make sure the base is at ground with the switch open. It wouldn't affect the "on" operation, because it would sink only 0.06mA from the base circuit.

There are certain cautions to be observed when designing transistor switches:

1. Choose the base resistor conservatively to get plenty of excess base current, especially when driving lamps, because of the reduced beta at low V_{CE}. This is also a good idea for high-speed switching, because of capacitive effects and reduced beta at very high frequencies (many megahertz). A small "speedup" capacitor is often connected across the base resistor to improve high-speed performance.

2. If the load swings below ground for some reason (e.g., it is driven from ac, or it is inductive), use a diode in series with the collector (or a diode in the reverse direction to ground) to prevent collector-base conduction on negative swings.

3. For inductive loads, protect the transistor with a diode across the load, as shown in Figure 2.4. Without the diode the inductor will swing the collector to a large positive voltage when the switch is opened, most likely exceeding the collector-emitter breakdown voltage, as the inductor tries to maintain its "on" current from V_{CC} to the collector (see the discussion of inductors in Section 1.31).

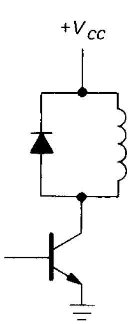

Figure 2.4. Always use a suppression diode when switching an inductive load.

Transistor switches enable you to switch very rapidly, typically in a small fraction of a microsecond. Also, you can switch many different circuits with a single control signal. One further advantage is the possibility of remote *cold switching*, in which only dc control voltages snake around through cables to reach front-panel switches, rather than the electronically inferior approach of having the signals themselves traveling through cables and switches (if you run lots of signals through cables, you're likely to get capacitive pickup as well as some signal degradation).

"Transistor man"

Figure 2.5 presents a cartoon that will help you understand some limits of transistor

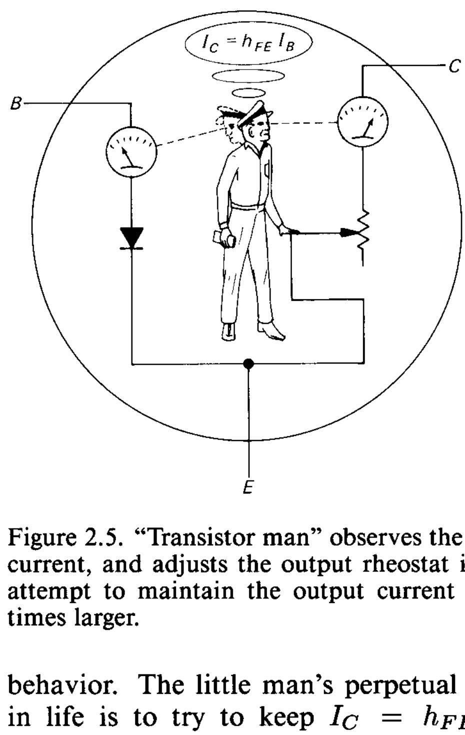

Figure 2.5. "Transistor man" observes the base current, and adjusts the output rheostat in an attempt to maintain the output current h_{FE} times larger.

behavior. The little man's perpetual task in life is to try to keep $I_C = h_{FE}I_B$; however, he is only allowed to turn the knob on the variable resistor. Thus he can go from a short circuit (saturation) to an open circuit (transistor in the "off" state), or anything in between, but he isn't allowed to use batteries, current sources, etc. One warning is in order here: Don't think that the collector of a transistor