small capacitor results in a high voltage. If the voltage exceeds the breakdown voltage of the gate's insulating silicon dioxide, it will break through and cause permanent damage to the FET. This is why MOS devices are particularly sensitive to static electricity. MOS components should be stored in conductive material that prevents the accumulation of charge on FET gate terminals.

Thus far, we have covered only enhancement-type MOSFETs. *Depletion-type* MOSFETs are built with a similar structure, but the channel region is doped with n-type silicon (in the case of an n-FET) so that the transistor conducts when $V_{GS} = 0$. Instead of defaulting to an open circuit, it conducts instead through the physically implanted channel. If positive V_{GS} is applied to a depletion-type n-FET, the channel is enhanced, and it can conduct more current as V_{DS} increases. However, if V_{GS} is made negative, the channel is depleted, and less current is conducted for a given V_{DS}. Schematic symbols for depletion-type MOSFETs are shown in Fig. 13.25. These devices are used in integrated circuits and are less common in discrete form.

Another type of FET, the *junction FET* (JFET) is not a MOS device and bears some similarity in structure to a BJT. As shown in Fig. 13.26, a JFET does not contain an insulated gate and does contain a physically implanted channel. Like a depletion-type MOSFET, a JFET conducts when $V_{GS} = 0$, and decreasing V_{GS} depletes the channel. As a result of the lack of gate insulation, the gate-drain and gate-source junctions will conduct when forward biased, thereby negating the transistor's operation. In the context of integrated circuits, JFETs are used mainly in bipolar analog processes, because they provide a higher input resistance as compared to BJTs.

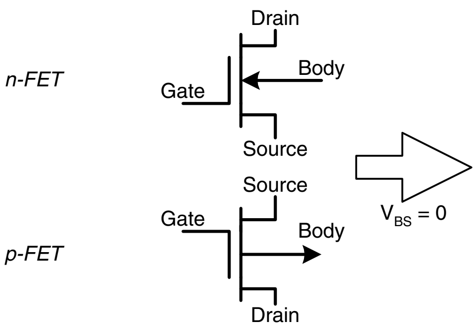

FIGURE 13.25 Depletion-type MOSFET graphical representations.

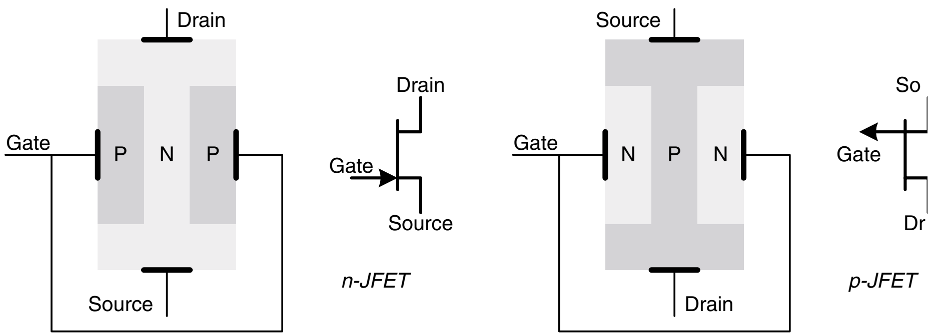

FIGURE 13.26 JFET structure and graphical representation.

CHAPTER 14
Operational Amplifiers

Transistors are the basic building blocks of solid-state amplifiers. Designing an amplifier using discrete transistors can be a substantial undertaking that requires theory outside the scope of this book. Operational amplifiers, or *op-amps,* exist to make the design of basic amplification circuits relatively easy. A digital engineer can use an op-amp to construct a general-purpose amplifier or active filter to preprocess an analog signal that may serve as input to the system. Comparators, which are based on op-amps, are useful in triggering events based on a signal reaching a certain threshold.

A key benefit of the op-amp is that it implements complex discrete transistor circuitry within a single integrated circuit and presents the engineer with a straightforward three-terminal amplifier that has well defined specifications and that can be externally configured to exhibit a wide range of characteristics.

Op-amps are presented here from three basic perspectives. First, the device is introduced using an idealized model so that its basic operation can be explained clearly without involving too many simultaneous details. The ideal op-amp is a very useful construct, because many real op-amp circuits can be treated as being ideal, as will be demonstrated later. Fundamental op-amp circuit analysis is stepped through in detail as part of the ideal presentation. The second section brings in nonideal device behavior and discusses how the idealized assumptions already introduced are affected in real circuits. The remainder of the chapter walks through a broad array of common op-amp circuit topologies with step-by-step analyses of their operation. The last of these presentations deals with the op-amp's cousin, the comparator, and explains the important topic of hysteresis.

14.1 THE IDEAL OP-AMP

The design of amplifiers is normally most relevant in analog circuits such as those found in audio and RF communications. An amplifier is an analog circuit that outputs a signal with greater amplitude than what is presented to it at the input. Amplification is sometimes necessary in digital systems. Amplifiers are often found at interfaces where the weak signal from a transducer (e.g., microphone or antenna) must be strengthened for sampling by an analog-to-digital converter. Even if a signal has sufficient amplitude, it may be desirable to scale it for better sampling resolution. For example, if an analog-to-digital converter accepts an input of 0 to 5 V and the incoming signal swings only between 0 and 3 V, 40 percent of the converter's resolution will be wasted. An amplifier can be used to scale the signal up to the full 5-V input range of the converter.

Solid-state amplifiers are constructed using transistors integrated onto a silicon chip or discrete transistors wired together on a circuit board. Amplifiers range greatly in complexity; complete AC analysis theory and its application to discrete amplifier design are outside the scope of this book. However, the design of many general-purpose amplifiers is made easier by the availability of prebuilt components called *operational amplifiers* (op-amps). Op-amps are so common that they are