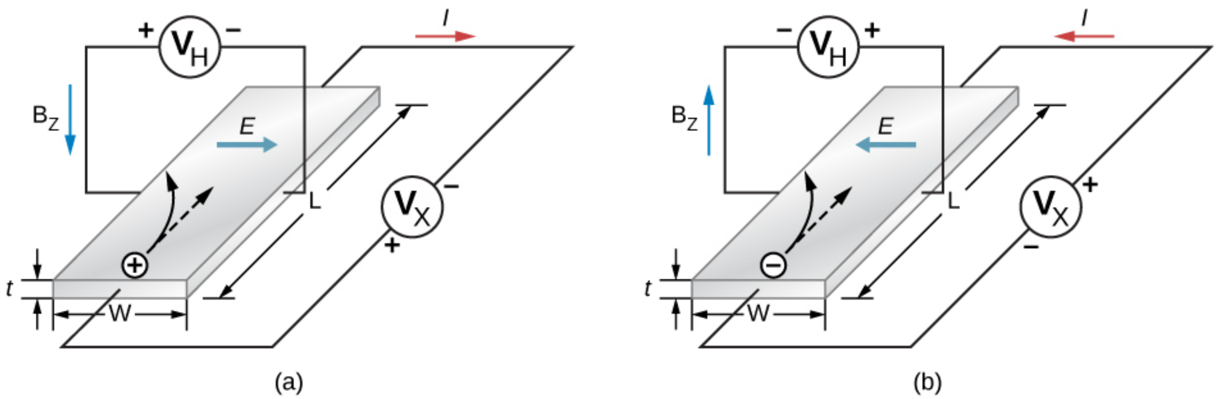

Figure 9.22 The Hall effect. (a) Positively charged electron holes are drawn to the left by a uniform magnetic field that points downward. An electric field is generated to the right. (b) Negative charged electrons are drawn to the left by a magnetic field that points up. An electric field is generated to the left.

9.7 | Semiconductor Devices

Learning Objectives

By the end of this section, you will be able to:

- Describe what occurs when n- and p-type materials are joined together using the concept of diffusion and drift current (zero applied voltage)
- Explain the response of a p-n junction to a forward and reverse bias voltage
- Describe the function of a transistor in an electric circuit
- Use the concept of a p-n junction to explain its applications in audio amplifiers and computers

Semiconductors have many applications in modern electronics. We describe some basic semiconductor devices in this section. A great advantage of using semiconductors for circuit elements is the fact that many thousands or millions of semiconductor devices can be combined on the same tiny piece of silicon and connected by conducting paths. The resulting structure is called an integrated circuit (ic), and ic chips are the basis of many modern devices, from computers and smartphones to the internet and global communications networks.

Diodes

Perhaps the simplest device that can be created with a semiconductor is a diode. A diode is a circuit element that allows electric current to flow in only one direction, like a one-way valve (see **Model of Conduction in Metals (http://cnx.org/content/m58730/latest/)**). A diode is created by joining a *p*-type semiconductor to an *n*-type semiconductor (**Figure 9.23**). The junction between these materials is called a ***p-n*** **junction**. A comparison of the energy bands of a silicon-based diode is shown in **Figure 9.23**(b). The positions of the valence and conduction bands are the same, but the impurity levels are quite different. When a *p*-*n* junction is formed, electrons from the conduction band of the *n*-type material diffuse to the *p*-side, where they combine with holes in the valence band. This migration of charge leaves positive ionized donor ions on the *n*-side and negative ionized acceptor ions on the *p*-side, producing a narrow double layer of charge at the *p*-*n* junction called the **depletion layer**. The electric field associated with the depletion layer prevents further diffusion. The potential energy for electrons across the *p*-*n* junction is given by **Figure 9.24**.

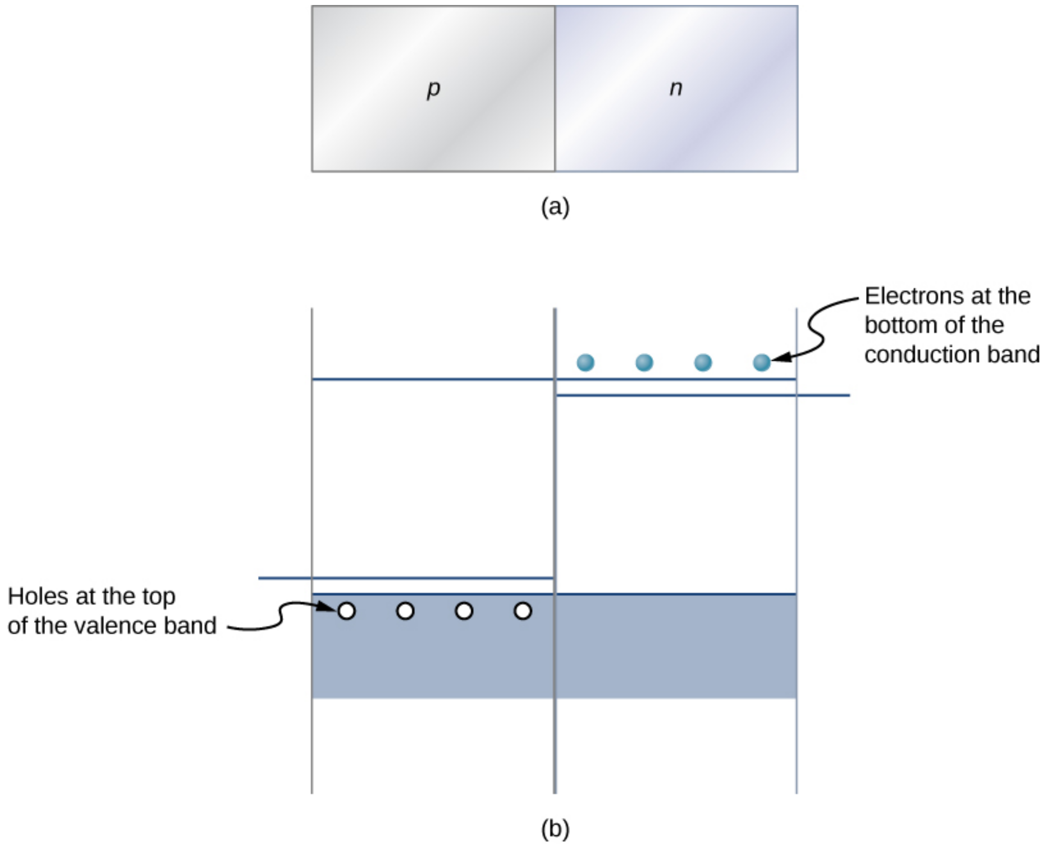

Figure 9.23 (a) Representation of a *p*-*n* junction. (b) A comparison of the energy bands of *p*-type and *n*-type silicon prior to equilibrium.

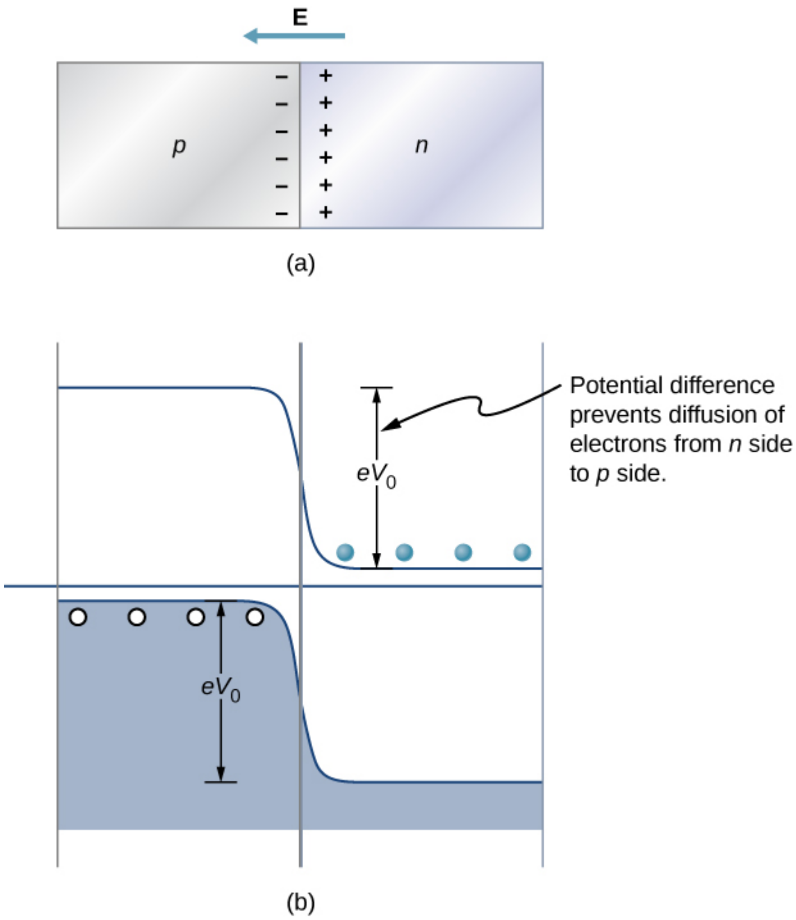

Figure 9.24 At equilibrium, (a) excess charge resides near the interface and the net current is zero, and (b) the potential energy difference for electrons (in light blue) prevents further diffusion of electrons into the *p*-side.

The behavior of a semiconductor diode can now be understood. If the positive side of the battery is connected to the *n*-type material, the depletion layer is widened, and the potential energy difference across the *p*-*n* junction is increased. Few or none of the electrons (holes) have enough energy to climb the potential barrier, and current is significantly reduced. This is called the **reverse bias configuration**. On the other hand, if the positive side of a battery is connected to the *p*-type material, the depletion layer is narrowed, the potential energy difference across the *p*-*n* junction is reduced, and electrons (holes) flow easily. This is called the **forward bias configuration** of the diode. In sum, the diode allows current to flow freely in one direction but prevents current flow in the opposite direction. In this sense, the semiconductor diode is a one-way valve.

We can estimate the mathematical relationship between the current and voltage for a diode using the electric potential concept. Consider N negatively charged majority carriers (electrons donated by impurity atoms) in the *n*-type material and a potential barrier V across the *p*-*n* junction. According to the Maxwell-Boltzmann distribution, the fraction of electrons that have enough energy to diffuse across the potential barrier is $Ne^{-eV/k_B T}$. However, if a battery of voltage V_b is applied in the forward-bias configuration, this fraction improves to $Ne^{-e(V - V_b)/k_B T}$. The electric current due to the majority carriers from the *n*-side to the *p*-side is therefore

$$I = Ne^{-eV/k_B T} e^{eV_b/k_B T} = I_0 e^{eV_b/k_B T}, \tag{9.35}$$

where I_0 is the current with no applied voltage and T is the temperature. Current due to the minority carriers (thermal excitation of electrons from the valence band to the conduction band on the *p*-side and subsequent attraction to the *n*-side) is $-I_0$, independent of the bias voltage. The net current is therefore

$$I_{net} = I_0 \left(e^{eV_b/k_B T} - 1 \right). \quad (9.36)$$

A sample graph of the current versus bias voltage is given in **Figure 9.25**. In the forward bias configuration, small changes in the bias voltage lead to large changes in the current. In the reverse bias configuration, the current is $I_{net} \approx -I_0$. For extreme values of reverse bias, the atoms in the material are ionized which triggers an avalanche of current. This case occurs at the **breakdown voltage**.

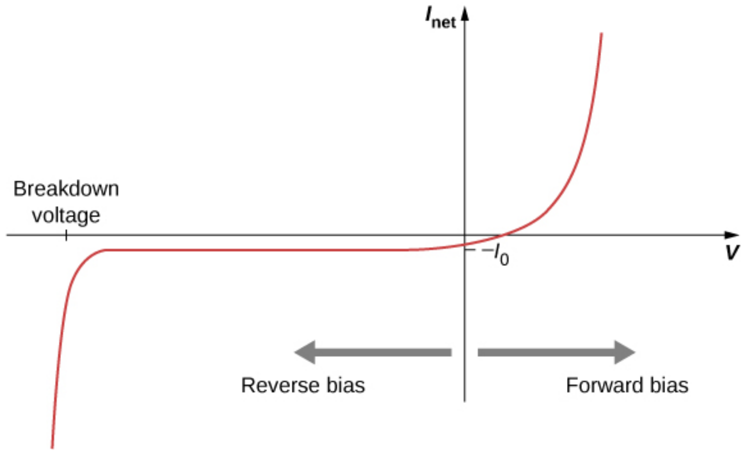

Figure 9.25 Current versus voltage across a *p*-*n* junction (diode). In the forward bias configuration, electric current flows easily. However, in the reverse bias configuration, electric current flow very little.

Example 9.6

Diode Current

Attaching the positive end of a battery to the *p*-side and the negative end to the *n*-side of a semiconductor diode produces a current of 4.5×10^{-1} A. The reverse saturation current is 2.2×10^{-8} A. (The reverse saturation current is the current of a diode in a reverse bias configuration such as this.) The battery voltage is 0.12 V. What is the diode temperature?

Strategy

The first arrangement is a forward bias configuration, and the second is the reverse bias configuration. In either case, **Equation 9.2** gives the current.

Solution

The current in the forward and reverse bias configurations is given by

$$I_{net} = I_0 \left(e^{eV_b/k_B T} - 1 \right).$$

The current with no bias is related to the reverse saturation current by

$$I_0 \approx -I_{sat} = 2.2 \times 10^{-8}.$$

Therefore

$$\frac{I_{net}}{I_0} = \frac{4.5 \times 10^{-1}\ \text{A}}{2.2 \times 10^{-8}\ \text{A}} = 2.0 \times 10^{8}.$$

Equation 9.2 can be written as

$$\frac{I_{\text{net}}}{I_0} + 1 = e^{eV_b/k_\text{B}T}.$$

This ratio is much greater than one, so the second term on the left-hand side of the equation vanishes. Taking the natural log of both sides gives

$$\frac{eV_b}{k_\text{B}T} = 19.$$

The temperature is therefore

$$T = \frac{eV_b}{k_\text{B}}\left(\frac{1}{19}\right) = \frac{e(0.12\text{ V})}{8.617 \times 10^{-5}\text{ eV/K}}\left(\frac{1}{19}\right) = 73\text{ K}.$$

Significance

The current moving through a diode in the forward and reverse bias configuration is sensitive to the temperature of the diode. If the potential energy supplied by the battery is large compared to the thermal energy of the diode's surroundings, $k_\text{B}T$, then the forward bias current is very large compared to the reverse saturation current.

9.5 Check Your Understanding How does the magnitude of the forward bias current compare with the reverse bias current?

Create a *p*-*n* junction and observe the behavior of a simple circuit for forward and reverse bias voltages. Visit this **site (https://openstaxcollege.org/l/21semiconductor)** to learn more about semiconductor diodes.

Junction Transistor

If diodes are one-way valves, transistors are one-way valves that can be carefully opened and closed to control current. A special kind of transistor is a junction transistor. A **junction transistor** has three parts, including an *n*-type semiconductor, also called the emitter; a thin *p*-type semiconductor, which is the base; and another *n*-type semiconductor, called the collector (**Figure 9.26**). When a positive terminal is connected to the *p*-type layer (the base), a small current of electrons, called the **base current** I_B, flows to the terminal. This causes a large **collector current** I_c to flow through the collector. The base current can be adjusted to control the large collector current. The current gain is therefore

$$I_c = \beta I_B. \tag{9.37}$$

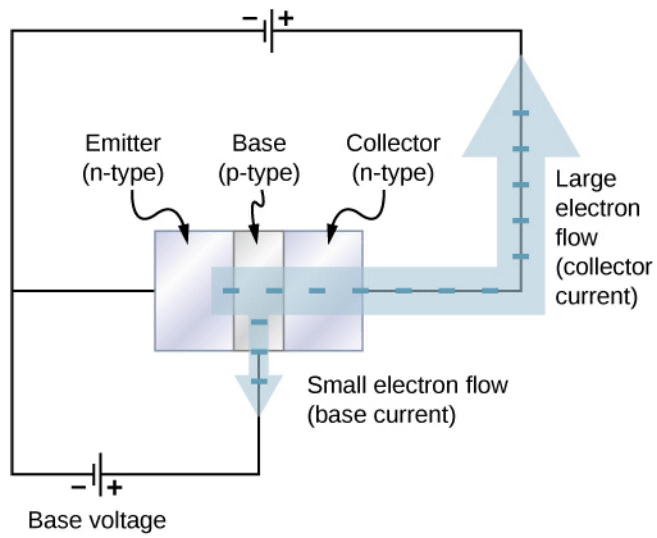

Figure 9.26 A junction transistor has three parts: emitter, base, and collector. Voltage applied to the base acts as a valve to control electric current from the emitter to the collector.

A junction transistor can be used to amplify the voltage from a microphone to drive a loudspeaker. In this application, sound waves cause a diaphragm inside the microphone to move in and out rapidly (**Figure 9.27**). When the diaphragm is in the "in" position, a tiny positive voltage is applied to the base of the transistor. This opens the transistor "valve" and allows a large electrical current flow to the loudspeaker. When the diaphragm is in the "out" position, a tiny negative voltage is applied to the base of the transistor, which shuts off the transistor valve so that no current flows to the loudspeaker. This shuts the transistor "valve" off so no current flows to the loudspeaker. In this way, current to the speaker is controlled by the sound waves, and the sound is amplified. Any electric device that amplifies a signal is called an **amplifier**.

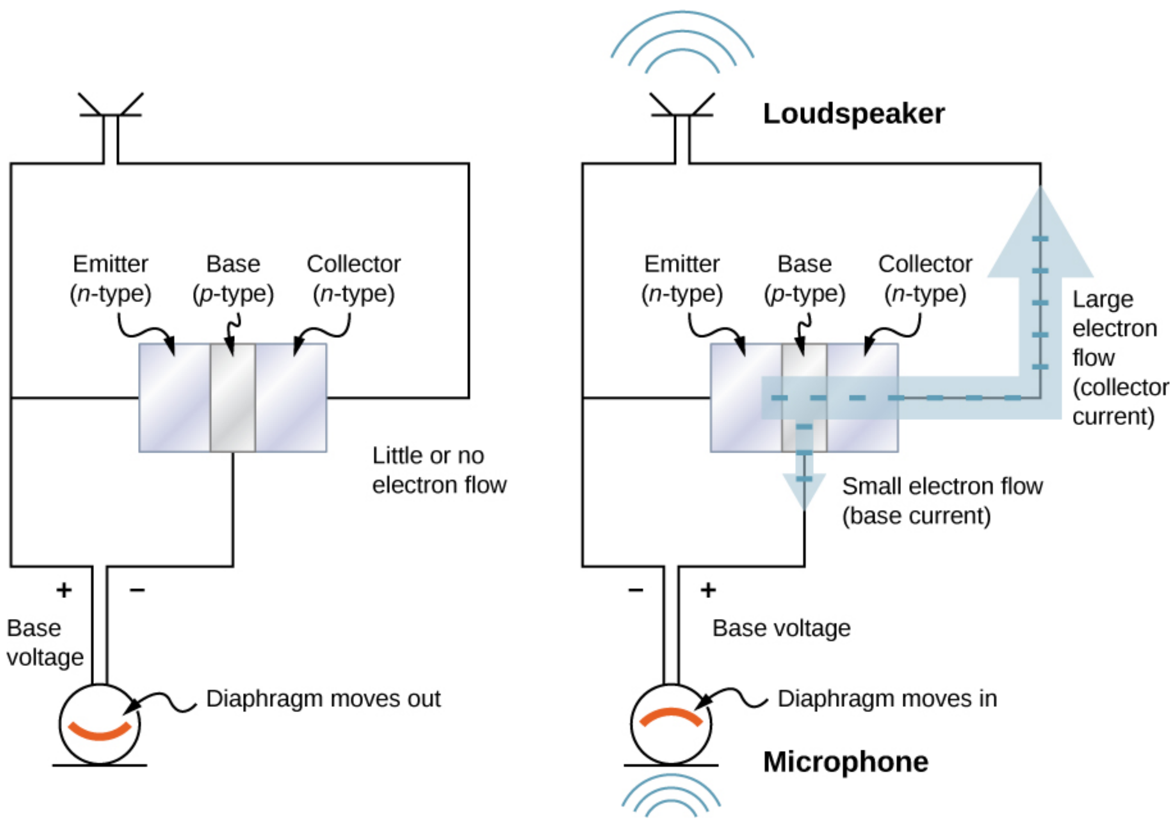

Figure 9.27 An audio amplifier based on a junction transistor. Voltage applied to the base by a microphone acts as a valve to control a larger electric current that passes through a loudspeaker.

In modern electronic devices, digital signals are used with diodes and transistors to perform tasks such as data manipulation. Electric circuits carry two types of electrical signals: analog and digital (**Figure 9.28**). An analog signal varies continuously, whereas a digital signal switches between two fixed voltage values, such as plus 1 volt and zero volts. In digital circuits like those found in computers, a transistor behaves like an on-off switch. The transistor is either on, meaning the valve is completely open, or it is off, meaning the valve is completely closed. Integrated circuits contain vast collections of transistors on a single piece of silicon. They are designed to handle digital signals that represent ones and zeroes, which is also known as binary code. The invention of the ic helped to launch the modern computer revolution.

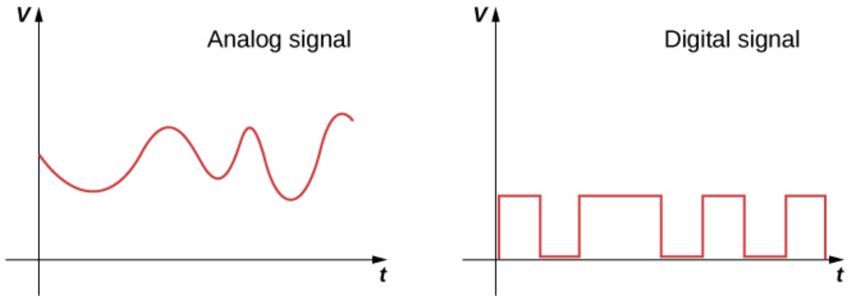

Figure 9.28 Real-world data are often analog, meaning data can vary continuously. Intensity values of sound or visual images are usually analog. These data are converted into digital signals for electronic processing in recording devices or computers. The digital signal is generated from the analog signal by requiring certain voltage cut-off value.

9.8 | Superconductivity

Learning Objectives

By the end of this section, you will be able to:

- Describe the main features of a superconductor
- Describe the BCS theory of superconductivity
- Determine the critical magnetic field for T = 0 K from magnetic field data
- Calculate the maximum emf or current for a wire to remain superconducting

Electrical resistance can be considered as a measure of the frictional force in electrical current flow. Thus, electrical resistance is a primary source of energy dissipation in electrical systems such as electromagnets, electric motors, and transmission lines. Copper wire is commonly used in electrical wiring because it has one of the lowest room-temperature electrical resistivities among common conductors. (Actually, silver has a lower resistivity than copper, but the high cost and limited availability of silver outweigh its savings in energy over copper.)

Although our discussion of conductivity seems to imply that all materials must have electrical resistance, we know that this is not the case. When the temperature decreases below a critical value for many materials, their electrical resistivity drops to zero, and the materials become superconductors (see **Superconductors (http://cnx.org/content/m58735/latest/)**).

Watch this **NOVA video (https://openstaxcollege.org/l/21NOVA)** excerpt, Making Stuff Colder, as an introduction to the topic of superconductivity and its many applications.

Properties of Superconductors

In addition to zero electrical resistance, superconductors also have perfect diamagnetism. In other words, in the presence of an applied magnetic field, the net magnetic field within a superconductor is always zero (**Figure 9.29**). Therefore, any magnetic field lines that pass through a superconducting sample when it is in its normal state are expelled once the sample becomes superconducting. These are manifestations of the Meissner effect, which you learned about in the chapter on current and resistance.