INTRODUCTION

In the previous chapter we dealt almost entirely with linear circuits; any nonlinearity, such as that introduced by amplifier output saturation, was considered a problem to be solved by the circuit designer. However, there are many other signal-processing functions that can be implemented only by nonlinear circuits. Examples include the generation of dc voltages from the ac power supply and the generation of signals of various waveforms (e.g., sinusoids, square waves, pulses, etc.). Also, digital logic and memory circuits constitute a special class of nonlinear circuits.

The simplest and most fundamental nonlinear circuit element is the diode. Just like a resistor, the diode has two terminals; but unlike the resistor, which has a linear (straight-line) relationship between the current flowing through it and the voltage appearing across it, the diode has a nonlinear $i-v$ characteristic.

This chapter is concerned with the study of diodes. In order to understand the essence of the diode function, we begin with a fictitious element, the ideal diode. We then introduce the silicon junction diode, explain its terminal characteristics, and provide techniques for the analysis of diode circuits. The latter task involves the important subject of device modeling.
Our study of modeling the diode characteristics will lay the foundation for our study of modeling transistor operation in the next two chapters.

Of the many applications of diodes, their use in the design of rectifiers (which convert ac to dc) is the most common. Therefore we shall study rectifier circuits in some detail and briefly look at a number of other diode applications. Further nonlinear circuits that utilize diodes and other devices will be found throughout the book, but particularly in Chapter 13.

To understand the origin of the diode terminal characteristics, we consider its physical operation. Our study of the physical operation of the pn junction and of the basic concepts of semiconductor physics is intended to provide a foundation for understanding not only the characteristics of junction diodes but also those of the field-effect transistor, studied in the next chapter, and the bipolar junction transistor, studied in Chapter 5.

Although most of this chapter is concerned with the study of silicon pn-junction diodes, we briefly consider some specialized diode types, including the photodiode and the light-emitting diode. The chapter concludes with a description of the diode model utilized in the SPICE circuit-simulation program. We also present a design example that illustrates the use of SPICE simulation.

### 3.1 THE IDEAL DIODE

#### 3.1.1 Current–Voltage Characteristic

The ideal diode may be considered the most fundamental nonlinear circuit element. It is a two-terminal device having the circuit symbol of Fig. 3.1(a) and the \( i-v \) characteristic shown in Fig. 3.1(b). The terminal characteristic of the ideal diode can be interpreted as follows: If \( v < 0 \), then \( i = 0 \); and if \( v > 0 \), then \( i = 0 \). The reverse bias is used to limit the forward bias to small values.

![Diode Symbol and Characteristics](image)

**FIGURE 3.1** The ideal diode: (a) diode circuit symbol; (b) \( i-v \) characteristic; (c) equivalent circuit in the reverse direction; (d) equivalent circuit in the forward direction.
negative voltage (relative to the reference direction indicated in Fig. 3.1a) is applied to the
diode, no current flows and the diode behaves as an open circuit (Fig. 3.1c). Diodes operated
in this mode are said to be reverse biased, or operated in the reverse direction. An ideal
diode has zero current when operated in the reverse direction and is said to be cut off, or
simply off.

On the other hand, if a positive current (relative to the reference direction indicated in
Fig. 3.1a) is applied to the ideal diode, zero voltage drop appears across the diode. In other
words, the ideal diode behaves as a short circuit in the forward direction (Fig. 3.1d); it
passes any current with zero voltage drop. A forward-biased diode is said to be turned on, or
simply on.

From the above description it should be noted that the external circuit must be designed
to limit the forward current through a conducting diode, and the reverse voltage across a cutoff
diode, to predetermined values. Figure 3.2 shows two diode circuits that illustrate this point.
In the circuit of Fig. 3.2(a) the diode is obviously conducting. Thus its voltage drop will be
zero, and the current through it will be determined by the +10-V supply and the 1-kΩ resis-
tor as 10 mA. The diode in the circuit of Fig. 3.2(b) is obviously cut off, and thus its current
will be zero, which in turn means that the entire 10-V supply will appear as reverse bias
across the diode.

The positive terminal of the diode is called the anode and the negative terminal the
cathode, a carryover from the days of vacuum-tube diodes. The \( i-v \) characteristic of the
ideal diode (conducting in one direction and not in the other) should explain the choice of its
arrow-like circuit symbol.

As should be evident from the preceding description, the \( i-v \) characteristic of the ideal
diode is highly nonlinear; although it consists of two straight-line segments, they are at 90°
to one another. A nonlinear curve that consists of straight-line segments is said to be piece-
wise linear. If a device having a piecewise-linear characteristic is used in a particular appli-
cation in such a way that the signal across its terminals swings along only one of the linear
segments, then the device can be considered a linear circuit element as far as that particular
circuit application is concerned. On the other hand, if signals swing past one or more of the
break points in the characteristic, linear analysis is no longer possible.

3.1.2 A Simple Application: The Rectifier
A fundamental application of the diode, one that makes use of its severely nonlinear \( i-v \)
curve, is the rectifier circuit shown in Fig. 3.3(a). The circuit consists of the series connection
of a diode $D$ and a resistor $R$. Let the input voltage $v_i$ be the sinusoid shown in Fig. 3.3(b), and assume the diode to be ideal. During the positive half-cycles of the input sinusoid, the positive $v_i$ will cause current to flow through the diode in its forward direction. It follows that the diode voltage $v_D$ will be very small—ideally zero. Thus the circuit will have the equivalent shown in Fig. 3.3(c), and the output voltage $v_o$ will be equal to the input voltage $v_i$. On the other hand, during the negative half-cycles of $v_i$, the diode will not conduct. Thus the circuit will have the equivalent shown in Fig. 3.3(d), and $v_o$ will be zero. Thus the output voltage will have the waveform shown in Fig. 3.3(e). Note that while $v_i$ alternates in polarity and has a zero average value, $v_o$ is unidirectional and has a finite average value or a dc component. Thus the circuit of Fig. 3.3(a) rectifies the signal and hence is called a rectifier. It can be used to generate dc from ac. We will study rectifier circuits in Section 3.5.
EXERCISES

3.1 For the circuit in Fig. 3.3(a), sketch the transfer characteristic $v_D$ versus $v_I$.
   Ans. See Fig. E3.1.

![Figure E3.1](image)

3.2 For the circuit in Fig. 3.3(a), sketch the waveform of $v_D$.
   Ans. See Fig. E3.2.

![Figure E3.2](image)

3.3 In the circuit of Fig. 3.3(a), let $v_I$ have a peak value of 10 V and $R = 1 \text{k} \Omega$. Find the peak value of $i_D$ and the dc component of $v_D$.
   Ans. 10 mA; 3.18 V

EXAMPLE

Figure 3.4(a) shows a circuit for charging a 12-V battery. If $v_D$ is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diode conducts. Also, find the peak value of the diode current and the maximum reverse-bias voltage that appears across the diode.
FIGURE 3.4  Circuit and waveforms for Example 3.1.

Solution
The diode conducts when $v_s$ exceeds 12 V, as shown in Fig. 3.4(b). The conduction angle is $2\theta$, where $\theta$ is given by

$$24 \cos \theta = 12$$

Thus $\theta = 60^\circ$ and the conduction angle is 120°, or one-third of a cycle.

The peak value of the diode current is given by

$$I_d = \frac{24 - 12}{100} = 0.12 \text{ A}$$

The maximum reverse voltage across the diode occurs when $v_s$ is at its negative peak and is equal to $24 + 12 = 36 \text{ V}$.

3.1.3 Another Application: Diode Logic Gates
Diodes together with resistors can be used to implement digital logic functions. Figure 3.5 shows two diode logic gates. To see how these circuits function, consider a positive-logic system in which voltage values close to 0 V correspond to logic 0 (or low) and voltage values

FIGURE 3.5  Diode logic gates: (a) OR gate; (b) AND gate (in a positive-logic system).
close to +5 V correspond to logic 1 (or high). The circuit in Fig. 3.5(a) has three inputs, \( v_A \), \( v_B \), and \( v_C \). It is easy to see that diodes connected to +5-V inputs will conduct, thus clamping the output \( v_Y \) to a value equal to +5 V. This positive voltage at the output will keep the diodes whose inputs are low (around 0 V) cut off. Thus the output will be high if one or more of the inputs are high. The circuit therefore implements the logic OR function, which in Boolean notation is expressed as

\[
Y = A + B + C
\]

Similarly, the reader is encouraged to show that using the same logic system mentioned above, the circuit of Fig. 3.5(b) implements the logic AND function,

\[
Y = A \cdot B \cdot C
\]

Assuming the diodes to be ideal, find the values of \( I \) and \( V \) in the circuits of Fig. 3.6.

**Solution**

In these circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such a case, we make a plausible assumption, proceed with the analysis, and then check whether we end up with a consistent solution. For the circuit in Fig. 3.6(a), we shall assume that both diodes are conducting. It follows that \( v_B = 0 \) and \( V = 0 \). The current through \( D_2 \) can now be determined from

\[
I_{D_2} = \frac{10 - 0}{10} = 1 \text{ mA}
\]
Writing a node equation at B,
\[ I + 1 = \frac{0 - (-10)}{5} \]
results in \( I = 1 \) mA. Thus \( D_1 \) is conducting as originally assumed, and the final result is \( I = 1 \) mA and \( V = 0 \) V.

For the circuit in Fig. 3.6(b), if we assume that both diodes are conducting, then \( V_B = 0 \) and \( V = 0 \). The current in \( D_2 \) is obtained from
\[ I_{D2} = \frac{10 - 0}{5} = 2 \text{ mA} \]
The node equation at B is
\[ I + 2 = \frac{0 - (-10)}{10} \]
which yields \( I = -1 \) mA. Since this is not possible, our original assumption is not correct. We start again, assuming that \( D_1 \) is off and \( D_2 \) is on. The current \( I_{D2} \) is given by
\[ I_{D2} = \frac{10 - (-10)}{15} = 1.33 \text{ mA} \]
and the voltage at node B is
\[ V_B = -10 \times 1.33 = +3.3 \text{ V} \]
Thus \( D_1 \) is reverse biased as assumed, and the final result is \( I = 0 \) and \( V = 3.3 \) V.

**EXERCISES**

3.4 Find the values of \( I \) and \( V \) in the circuits shown in Fig. E3.4.
3.2 TERMINAL CHARACTERISTICS OF JUNCTION DIODES

3.5 Figure E3.5 shows a circuit for an ac voltmeter. It utilizes a moving-coil meter that gives a full-scale reading when the average current flowing through it is 1 mA. The moving-coil meter has a 50-Ω resistance.

\[ + \]
\[ R \]
\[ v_i \]
\[ \text{Moving-coil meter} \]

**FIGURE E3.5**

Find the value of \( R \) that results in the meter indicating a full-scale reading when the input sine-wave voltage \( v_i \) is 20 V peak-to-peak. (Hint: The average value of half-sine waves is \( V_p/\pi \)).

**Ans.** 3.133 kΩ