3.1 DIODE CHARACTERISTICS

The diode is a very important electronic device that has two terminals: the **anode** and the **cathode**. The circuit symbol for a diode is shown in Figure 3.1a, and the diode volt-ampere characteristic is displayed in Figure 3.1b. As shown in Figure 3.1a, the voltage v_D across the diode is referenced as positive at the anode and negative at the cathode. Similarly, the diode current i_D is referenced as positive from anode to cathode.

... current flows easily through the diode in the direction of the arrowhead.

... for moderately negative values of v_D, the current i_D is very small.

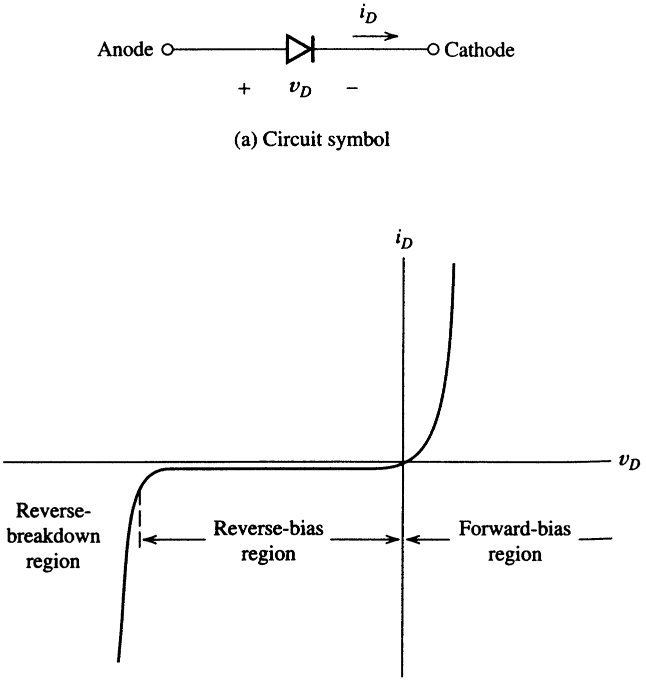
If a sufficiently large reverse-bias voltage is applied to the diode, ... currents of large magnitude flow.

Notice in the characteristic that if the voltage v_D across the diode is positive, relatively large amounts of current flow for small voltages. This condition is called **forward bias.** Thus, current flows easily through the diode in the direction of the arrowhead of the circuit symbol.

On the other hand, for moderately negative values of v_D, the current i_D is very small. This is called the **reverse-bias** region, as shown on the diode characteristic. If a sufficiently large reverse-bias voltage is applied to the diode, its operation enters the **reverse-breakdown** region of the characteristic, and currents of large magnitude flow. Provided that the power dissipated in the diode does not raise its temperature too high, reverse-breakdown operation is not destructive to the device. In fact, we will see that diodes are often deliberately operated in the reverse-breakdown region.

Small-Signal Diodes

Various materials and structures are used to fabricate diodes. For now, we confine our discussion to small-signal silicon diodes commonly found in low- and medium-power



(a) Circuit symbol

(b) Volt-ampere characteristic

Figure 3.1 Semiconductor diode.

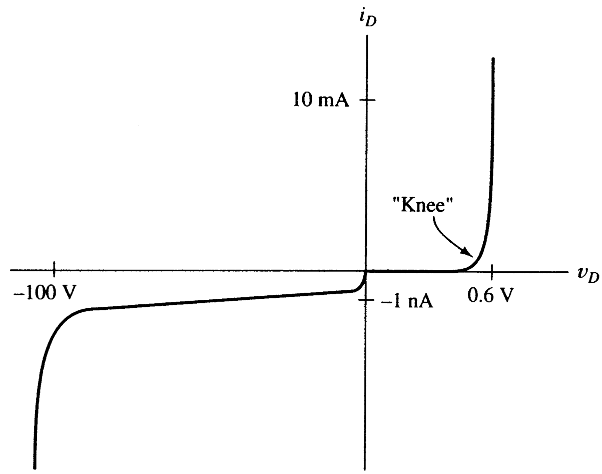


Figure 3.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the changes of scale.

electronic circuits. One such discrete diode is the 1N4148, which is available from several manufacturers. Integrated-circuit diodes have characteristics that are similar to small-signal discrete diodes.

The characteristic curve of a typical small-signal silicon diode operated at a temperature of 300 K is illustrated in Figure 3.2. Notice that the voltage and current scales for the forward-bias region are different than for the reverse-bias region. This helps to clearly display the details of the characteristic, because the current magnitudes are much smaller, and the voltage magnitudes much larger, in the reverse-bias region than in the forward-bias region.

In the forward-bias region, small-signal silicon diodes conduct very little current (much less than 1 mA), until a forward voltage of 0.6 to 0.7 V is applied (assuming that the diode is at a temperature of about 300 K). Then the current increases very rapidly as the voltage is increased further. We say that the forward characteristic displays a *knee* in the forward-bias characteristic at about 0.6 V. As the temperature increases, the knee voltage decreases by about 2 mV/K.

As the temperature increases, the knee voltage decreases by about 2 mV/K.

In the reverse-bias region, for small-signal silicon diodes at room temperature, a typical current is about 1 nA. As the temperature increases, the reverse current increases in magnitude. A rule of thumb is that the reverse current doubles for each 10-K increase in temperature.

A rule of thumb is that the reverse current doubles for each 10-K increase in temperature.

When reverse breakdown is reached, the current increases in magnitude very rapidly. The voltage for which this occurs is called the **breakdown voltage**. For example, the breakdown voltage of the diode characteristic illustrated in Figure 3.2 is approximately −100 V. Breakdown voltages range from several volts to several hundred volts. Some applications call for diodes that operate in the forward-bias and nonconducting reverse-bias regions without entering the breakdown region. Diodes intended for these applications have a specification for the minimum magnitude of the breakdown voltage.

Zener Diodes

Zener diodes are used in applications for which a constant voltage in breakdown is desirable.

Diodes that are intended to operate in the breakdown region are called **Zener diodes**. Zener diodes are used in applications for which a constant voltage in breakdown is desirable. Therefore, manufacturers try to optimize Zener diodes for a nearly vertical characteristic in the breakdown region. The modified diode symbol shown in Figure 3.3 is used for Zener diodes. Discrete Zener diodes are available with breakdown voltages specified to a tolerance of ±5%.

Figure 3.3 Zener diode symbol.

Actually, there are two mechanisms that can cause reverse breakdown. For diodes with breakdown greater than 6 V, a high-field effect known as **avalanche** is responsible. Thus, diodes with the higher breakdown voltages are properly called **avalanche diodes.** Below about 6 V, a quantum mechanical phenomenon known as tunneling is responsible for breakdown. Strictly speaking, Zener diodes are those in the lower breakdown range. However, in practice, both terms are used interchangeably for all breakdown diodes.

3.2 LOAD-LINE ANALYSIS

The volt-ampere characteristics of diodes are nonlinear. We will see in the next several chapters that characteristics of other electronic devices are also nonlinear. Because of this nonlinearity, many of the techniques you have learned in basic circuit theory courses for dealing with linear circuits do not apply to circuits involving diodes. In fact, much of your study of electronics will be concerned with techniques for analyzing circuits containing nonlinear elements.

Graphical methods provide one approach to analyzing circuits containing nonlinear elements.

Graphical methods provide one approach to analyzing these kinds of circuits. For example, consider the circuit shown in Figure 3.4. Applying Kirchhoff's voltage law, we can write

Load-line Equation.

$$V_{SS} = Ri_D + v_D \tag{3.1}$$

We assume that the values of V_{SS} and R are known and that we wish to find i_D and v_D. Thus, Equation (3.1) has two unknowns, and another relationship between i_D and v_D is needed to find a solution. The needed relationship is available in graphical form in Figure 3.5, which shows the volt–ampere characteristic of the diode.

We can obtain the solution by plotting Equation (3.1) on the same set of axes used for the diode characteristic. Because this equation is linear, it plots as a straight line that can be drawn if two points satisfying the equation are located. A simple method for locating these points is to assume that $i_D = 0$. Then Equation (3.1) yields $v_D = V_{SS}$. This pair of values is shown as point A in Figure 3.5. A second point results if we assume that $v_D = 0$, in which case the equation yields $i_D = V_{SS}/R$. This pair of values is shown as point B in Figure 3.5. Then, connecting points A and B results in the plot, which is called the **load line.** The **operating point** is the intersection of the load line and the diode characteristic. The operating point represents the simultaneous solution of Equation (3.1) and the diode characteristic.

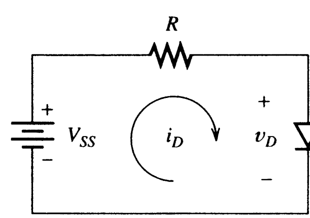


Figure 3.4 Circuit for load-line analysis.

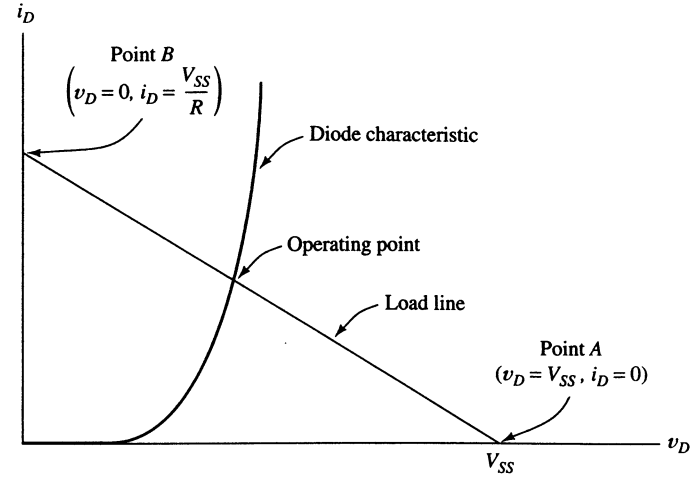


Figure 3.5 Load-line analysis of the circuit of Figure 3.4.

Example 3.1 Load-Line Construction for a Diode Circuit

If the circuit of Figure 3.4 has $V_{SS} = 2\,\text{V}$, $R = 1\,\text{k}\Omega$, and a diode with the characteristic shown in Figure 3.6, find the diode voltage and current at the operating point.

Locate two points on the load line, then draw a straight line through them.

SOLUTION First, we locate the ends of the load line. Substituting $v_D = 0$ and the values given for V_{SS} and R into Equation (3.1) yields $i_D = 2\,\text{mA}$. These values are plotted as point B in Figure 3.6. Substitution of $i_D = 0$ and $V_{SS} = 2\,\text{V}$ results in $v_D = 2\,\text{V}$. These values are plotted as point A in the figure. Constructing the load line results in an operating point of $v_D \cong 0.7\,\text{V}$ and $i_D \cong 1.3\,\text{mA}$, as shown in the figure. ❑

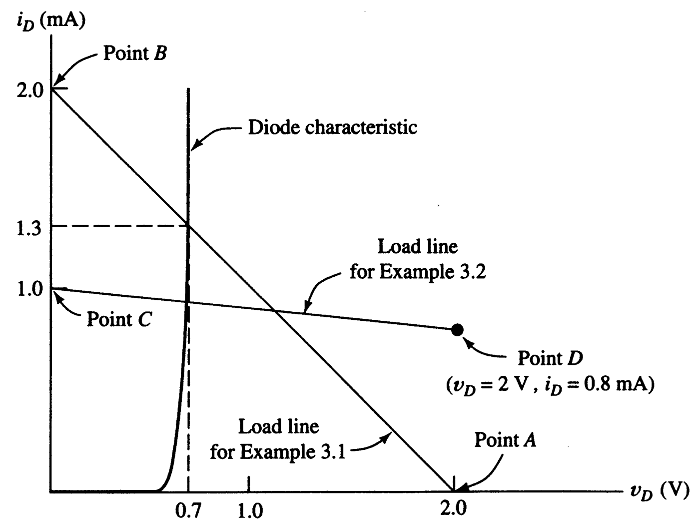


Figure 3.6 Load-line analysis for Examples 3.1 and 3.2.

Example 3.2 Construction When One End of the Line Falls Outside the Plot

Repeat Example 3.1 if $V_{SS} = 10\,\text{V}$ and $R = 10\,\text{k}\Omega$.

SOLUTION If we let $v_D = 0$ and substitute values into Equation (3.1), we find that $i_D = 1\,\text{mA}$. This is plotted as point C in Figure 3.6.

If we proceed as before by assuming that $i_D = 0$, we find that $v_D = 10\,\text{V}$. This is a perfectly valid point on the load line, but it plots far off the page. Of course, we can use any other point satisfying Equation (3.1) to locate the load line. Because we already have point C on the i_D axis, a good point to use would be one on the right-hand edge of Figure 3.6. Thus, we assume that $v_D = 2\,\text{V}$ and substitute values into Equation (3.1), resulting in $i_D = 0.8\,\text{mA}$. These values plot as point D. Then we draw the load line and find that the operating-point values are $v_D \cong 0.68\,\text{V}$ and $i_D \cong 0.93\,\text{mA}$. ❑

EXERCISE

3.1 Find the operating point for the circuit of Figure 3.4 if the diode characteristic is shown in Figure 3.7 and

(a) $V_{SS} = 2\,\text{V}$ and $R = 100\,\Omega$;

(b) $V_{SS} = 15\,\text{V}$ and $R = 1\,\text{k}\Omega$;

(c) $V_{SS} = 1.0\,\text{V}$ and $R = 20\,\Omega$.

Answer

(a) $v_D \cong 1.08\,\text{V}$, $i_D \cong 9.2\,\text{mA}$;

(b) $v_D \cong 1.18\,\text{V}$, $i_D \cong 13.8\,\text{mA}$;

(c) $v_D \cong 0.91\,\text{V}$, $i_D \cong 4.5\,\text{mA}$.

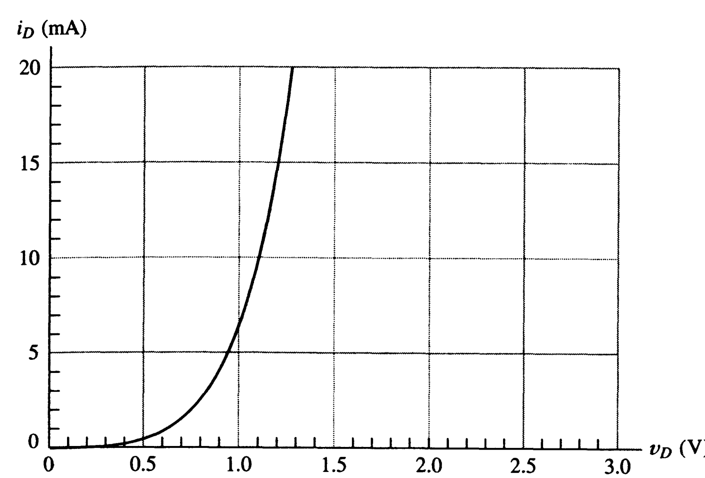


Figure 3.7 Diode characteristic for Exercise 3.1.

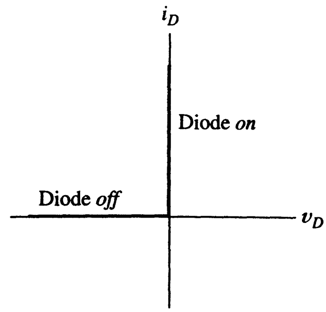


Figure 3.8 Ideal-diode volt–ampere characteristic.

3.3 THE IDEAL-DIODE MODEL

While load-line analysis of diode circuits provides insight and accurate results, we need simpler models in order to rapidly analyze circuits containing multiple diodes. One very useful model is the **ideal-diode model**, which is a perfect conductor with zero voltage drop in the forward direction. In the reverse direction, the ideal diode is an open circuit. We use the ideal-diode assumption if our judgment tells us that the forward diode voltage drop and reverse current are negligible or if we want a basic understanding, rather than an exact analysis, of a circuit. The volt–ampere characteristic for the ideal diode is illustrated in Figure 3.8. If i_D is positive, then v_D is zero, and we say that the diode is in the *on* state. On the other hand, if v_D is negative, then i_D is zero, and we say that the diode is in the *off* state.

We use the ideal-diode assumption if our judgment tells us that the forward diode voltage drop and reverse current are negligible or if we want a basic understanding, rather than an exact analysis, of a circuit.

Assumed States for Analysis of Ideal-Diode Circuits

When analyzing a circuit containing ideal diodes, we may not know in advance which diodes are on and which are off. Thus, we are forced to make considered guesses. Then we analyze the circuit to find the currents in the diodes assumed to be on and the voltages across the diodes assumed to be off. If i_D is positive for the diodes assumed to be on, and if v_D is negative for the diodes assumed to be off, our assumptions are correct and we have solved the circuit. (We are assuming that i_D is referenced as positive in the forward direction and v_D is referenced as positive at the anode.) Otherwise, we must make another assumption about the diodes and try again. After a little practice, your first guess will usually be correct, at least for simple circuits.

Step 1: Assume a set of states for the diodes.
Step 2: Solve the circuit to find i_D for diodes assumed to be on and v_D for diodes assumed to be off.
Step 3: Check to see if i_D is positive for all diodes assumed to be on and if v_D is negative for all diodes assumed to be off. If so the solution is complete; otherwise return to step 1.

Example 3.3 Circuit Solution by Assumed Diode States

Analyze the circuit illustrated in Figure 3.9a using the ideal-diode model.

SOLUTION

Step 1: We start by assuming that D_1 is off and D_2 is on.
Step 2: With D_1 off and D_2 on, the equivalent circuit is shown in Figure 3.9b. Solving results in $i_{D2} = 0.5\,\text{mA}$ and $v_{D1} = 7\,\text{V}$.
Step 3: Because the current in D_2 is positive, our assumption that D_2 is on seems to be correct. However, we also have $v_{D1} = +7\,\text{V}$, which is not consistent with the assumption that D_1 is off. Therefore, we must return to step 1 and try another assumption.

Step 1: This time we assume that D_1 is on and D_2 is off.
Step 2: The equivalent circuit for these assumptions is illustrated in Figure 3.9c. By solving this circuit, we find that $i_{D1} = 1\,\text{mA}$ and $v_{D2} = -3\,\text{V}$.
Step 3: These values are consistent with the assumptions about the diodes (D_1 on and D_2 off) and therefore are correct.

❑

... we cannot decide on the state of a particular diode until we have found a combination of states that works for all of the diodes in the circuit.

Notice in Example 3.3 that even though the current flows in the forward direction of D_2 for our first guess about diode states, the correct solution is that D_2 is off. Thus, in general, we cannot decide on the state of a particular diode until we have found a combination of states that works for all of the diodes in the circuit.

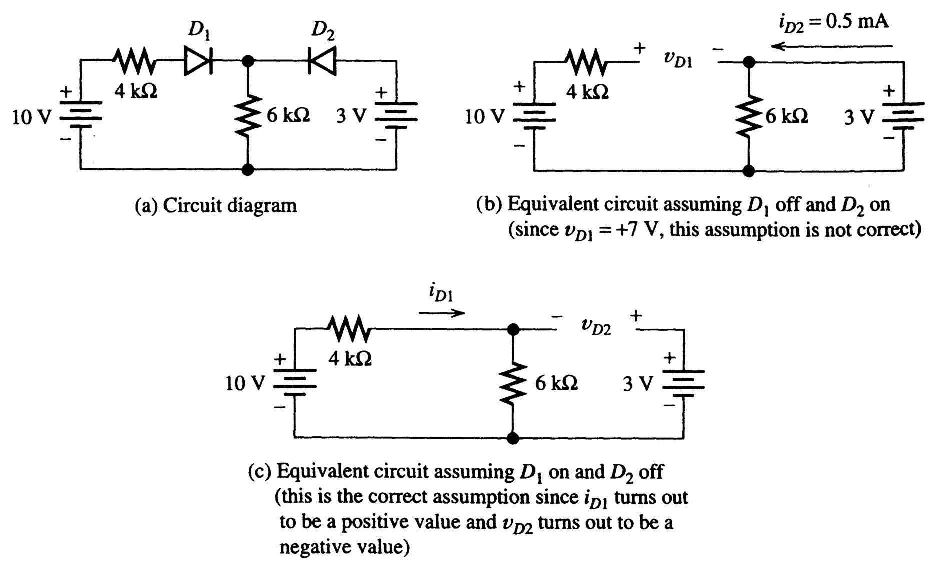
For a circuit containing n diodes, there are 2^n possible states. Thus, an exhaustive search eventually yields the solution.

EXERCISE

3.2 Show that the condition D_1 off and D_2 off is not valid for the circuit of Figure 3.9a.

EXERCISE

3.3 Show that the condition D_1 on and D_2 on is not valid for the circuit of Figure 3.9a.



(a) Circuit diagram

(b) Equivalent circuit assuming D_1 off and D_2 on (since $v_{D1} = +7$ V, this assumption is not correct)

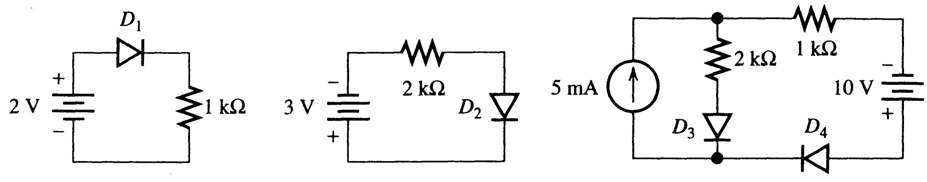
(c) Equivalent circuit assuming D_1 on and D_2 off (this is the correct assumption since i_{D1} turns out to be a positive value and v_{D2} turns out to be a negative value)

Figure 3.9 Analysis of a diode circuit using the ideal-diode model. See Example 3.3.

EXERCISE

3.4 Determine the diode states for the circuits shown in Figure 3.10. Assume ideal diodes.

Answer (a) D_1 is on; (b) D_2 is off; (c) D_3 is off and D_4 is on.



(a) (b) (c)

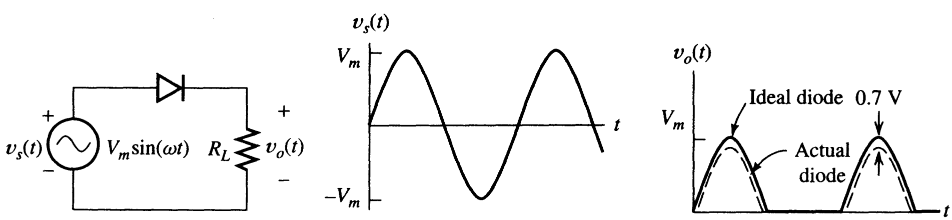
Figure 3.10 Circuits for Exercise 3.4.

3.4 RECTIFIER CIRCUITS

Now that we have introduced the diode and two methods for analyzing diode circuits, we consider some practical circuits. First, we examine several types of **rectifiers** that convert ac power into dc power. Rectifiers form the basis for electronic power supplies and battery-charging circuits. Rectifiers also are used in signal processing (e.g., to demodulate a radio signal) and in the precision conversion of an ac voltage to dc in an electronic voltmeter.

Half-Wave Rectifier Circuits

A **half-wave rectifier** with a sinusoidal source and resistive load is shown in Figure 3.11. When the source voltage $v_s(t)$ is positive, the diode is in the forward-bias region. Then if an ideal diode is assumed, the source voltage appears across the load. For a typical real



(a) Circuit diagram (b) Source voltage versus time (c) Load voltage versus time

Figure 3.11 Half-wave rectifier with resistive load.

diode, the output voltage is less than the source voltage by an amount equal to the drop across the diode, which is about 0.7 V for silicon diodes at room temperature. If the source voltage is negative, the diode is reverse biased and no current flows through the load. Even for typical real diodes, only a very small reverse current flows. Thus, only the positive half-cycles of the source voltage appear across the load.

Half-Wave Rectifier with Smoothing Capacitor

Often, we want to convert an ac voltage into a nearly constant dc voltage that is to be used as a power supply for electronic circuits. One approach to smoothing the rectifier output voltage is to place a large capacitance across the output terminals of the rectifier. The circuit and waveforms of current and voltage are shown in Figure 3.12. When the ac source reaches a positive peak, the capacitor is charged to the peak voltage (assuming an ideal diode). Then, when the source voltage drops below the voltage stored on the capacitor, the diode is reverse biased and no current flows through it. The capacitor continues to supply current to the load, slowly discharging until the next positive peak of the ac input. As shown in the figure, current flows through the diode in pulses that recharge the capacitor.

Because of the charge-and-discharge cycle, the load voltage contains a small ac component called **ripple**. Usually, it is desirable to minimize ripple, so we choose the largest capacitance value that is practical. In this case, the capacitor discharges for nearly the entire cycle, and the charge removed from the capacitor during one discharge cycle is

$$Q \cong I_L T \tag{3.2}$$

where I_L is the average load current and T is the period of the ac voltage. Since the charge removed from the capacitor is the product of the change in voltage and the capacitance, we can also write

$$Q = V_r C \tag{3.3}$$

where V_r is the peak-to-peak ripple voltage and C is the capacitance. Equating the right-hand sides of Equations (3.2) and (3.3) allows us to solve for C:

Equation for estimating the filter capacitance needed in a half-wave rectifier.

$$C = \frac{I_L T}{V_r} \tag{3.4}$$

In practice, Equation (3.4) is approximate, because the load current may vary with time and because the capacitor does not discharge for a complete cycle. However, in the design of power-supply circuits, this equation gives a good starting value for the capacitance. Of course, we can use computer simulation to refine the capacitance value.

The average voltage supplied to the load is approximately midway between the minimum and maximum voltages. Thus, referring to Figure 3.12, we see that the average load voltage is

$$V_L \cong V_m - \frac{V_r}{2} \tag{3.5}$$

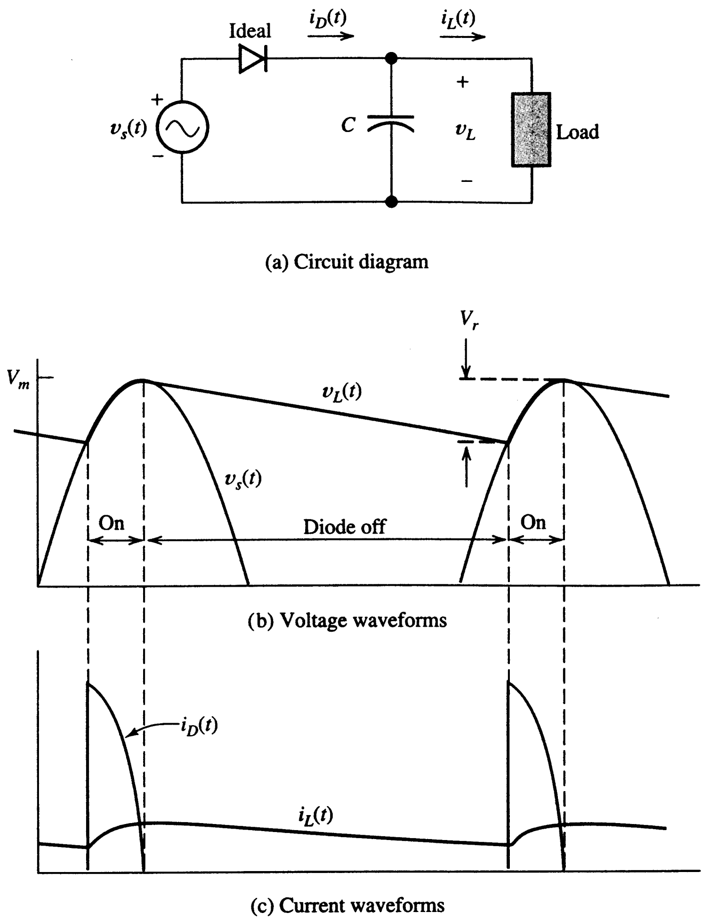


Figure 3.12 Half-wave rectifier with smoothing capacitor.

Peak Inverse Voltage

An important aspect of rectifier circuits is the **peak inverse voltage** (PIV) across the diodes. Of course, the breakdown specification of the diodes should be greater in magnitude than the PIV. For example, in the half-wave circuit with a resistive load, shown in Figure 3.11, the PIV is V_m.

Now, referring to Figure 3.12 for the negative peak of the ac input, we see that the reverse bias of the diode is the sum of the source voltage and the voltage stored on the capacitor. Thus by adding a smoothing capacitor in parallel with the load, the PIV is increased to (approximately) $2V_m$.

Full-Wave Rectifier Circuits

Several **full-wave rectifier** circuits are in common use. One approach uses a center-tapped transformer and two diodes, as shown in Figure 3.13. This circuit consists of two half-wave rectifiers with out-of-phase source voltages and a common load. The diodes conduct on alternate half cycles.

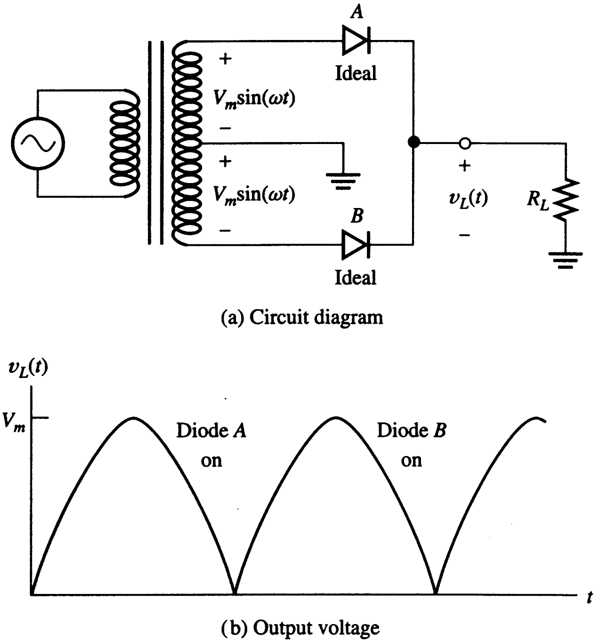


Figure 3.13
Full-wave rectifier.

A transformer allows the input of the rectifier to be selected by the designer. Furthermore, a transformer isolates the load from the ac power line.

Besides providing the out-of-phase ac voltages, the transformer also allows V_m to be adjusted by selecting the turns ratio. This is an important function because the ac voltage that is available is often not of a suitable amplitude for direct rectification—usually either a higher or lower dc voltage is required.

A second type of full-wave rectifier uses the **diode bridge** shown in Figure 3.14. When the ac voltage is positive at the top of the secondary winding, current flows through diode A, then through the load, and returns through diode B, as shown in the figure. For the opposite polarity, current flows through diodes D and C. Notice that in either case, current flows in the same direction through the load.

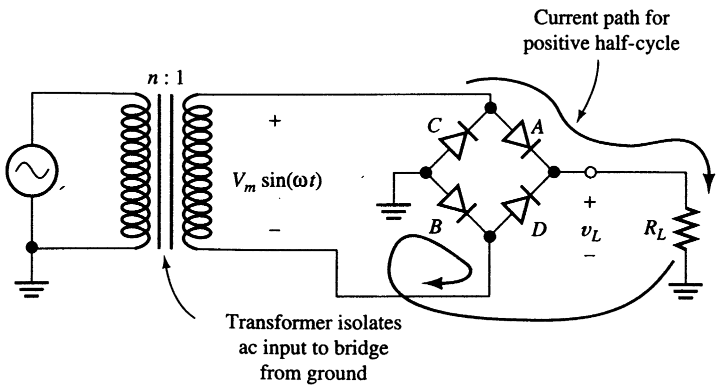


Figure 3.14 Diode-bridge full-wave rectifier.

Usually, a transformer is used, so that neither of the input terminals of the bridge are connected to ground. This is necessary if one side of the load is to be connected to ground as shown in the figure.

If we wish to smooth the voltage across the load, a capacitor can be placed in parallel with the load, as in the half-wave circuit discussed earlier. In full-wave circuits, the capacitor discharges for only a half-cycle before being recharged. Thus, the required capacitance is only half as much in the full-wave circuit as in the half-wave circuit. Therefore, we modify Equation (3.4) for the full-wave rectifier to obtain

$$C = \frac{I_L T}{2V_r} \tag{3.6}$$

Equation for estimating the filter capacitance needed in a full-wave rectifier.

EXERCISE

3.5 A power-supply circuit is needed to deliver 0.1 A and an average of 15 V to a load. The ac source available is 110 V rms with a frequency of 60 Hz. Assume that the full-wave circuit of Figure 3.14 is to be used with a smoothing capacitor in parallel with the load. The peak-to-peak ripple voltage is to be 0.4 V. Allow 0.7 V for forward diode drop. Find the turns ratio n that is needed and the approximate value of the smoothing capacitor. (*Hint:* To achieve an average load voltage of 15 V with a ripple of 0.4 V, design for a peak load voltage of 15.2 V.)

Answer $n = 9.37$, $C = 2083\,\mu\text{F}$.

EXERCISE

3.6 Repeat Exercise 3.5 using the circuit of Figure 3.13 with a smoothing capacitor in parallel with R_L. (Define the turns ratio as the ratio of the number of primary turns to the number of secondary turns between the center tap and one end.)

Answer $n = 9.79$, $C = 2083\,\mu\text{F}$.

3.5 WAVE-SHAPING CIRCUITS

A wide variety of **wave-shaping circuits** are useful in electronic systems. These circuits transform one waveform into another. Wave-shaping circuits are employed in function generators used to generate electrical test signals. Typically, an oscillator generates a square wave that is passed through an integrator (see Section 2.11), resulting in a triangular waveform. Then the triangular waveform is passed through a carefully designed wave-shaping circuit to produce a sinusoidal waveform. All three waveforms are available to the user. Numerous examples of wave-shaping circuits can be found in transmitters and receivers for television or radar.

Numerous examples of wave-shaping circuits can be found in transmitters and receivers for television or radar.

EXERCISE

3.16 At a temperature of 300 K, a certain junction diode has $i_D = 0.1$ mA for $v_D = 0.6$ V. Assume that n is unity and use $V_T = 0.026$ V. Find the value of the saturation current I_s. Then compute the diode current at $v_D = 0.65$ V and at 0.70 V. [*Hint:* Because $v_D > 0.1$ V, we have $i_D \cong I_s \exp(v_D/nV_T)$.]

Answer $I_s = 9.50 \times 10^{-15}$ A, $i_D = 0.684$ mA, $i_D = 4.68$ mA.

EXERCISE

3.17 Consider a diode under forward bias, so that $i_D \cong I_s \exp(v_D/nV_T)$. Assume that $V_T = 0.026$ V and $n = 1$. (a) By what increment must v_D increase to double the current? (b) To increase the current by a factor of 10?

Answer (a) $\Delta v_D = 18$ mV; (b) $\Delta v_D = 59.9$ mV.

3.9 BASIC SEMICONDUCTOR CONCEPTS

In this section and the next, we discuss basic semiconductor physics and internal operation of diodes. Our discussion of device physics is brief and mostly of a qualitative nature. It is intended to give you a framework for understanding diode and transistor behavior—particularly high-frequency and switching characteristics.

A qualitative knowledge of semiconductor physics helps us to understand diode and transistor behavior, especially in high-speed digital logic circuits.

Several materials are useful for the fabrication of solid-state electronic devices—most notably, silicon (Si), germanium (Ge), and gallium arsenide (GaAs). Because of the widespread use of silicon, we reference most of our discussion to it. At least on a qualitative basis, the physics of other semiconductors is similar to that of silicon.

Intrinsic Silicon

The Bohr model of an isolated silicon atom consists of a nucleus containing 14 protons and most of the mass of the atom. A total of 14 electrons surround the nucleus in specific orbits. The electron orbits occur in groups known as **shells**. The innermost (lowest energy) shell consists of two orbits. The next highest energy shell contains eight orbits. Each orbit can contain at most a single electron. Thus, for a silicon atom in its lowest energy state, the innermost shell contains two electrons, the next higher shell contains eight electrons, and the remaining four electrons occupy orbits in the outermost shell, also called the **valence shell**. It is these outermost valence electrons that provide the moving charge carriers in the solid form of the material.

In an **intrinsic** (i.e., pure) silicon crystal, each atom takes up a lattice position having four nearest neighboring atoms. Each pair of neighboring atoms forms a **covalent bond** consisting of two electrons that orbit around the pair. Each atom contributes one electron to each of the four bonds with its neighbors. This is illustrated by the simple planar

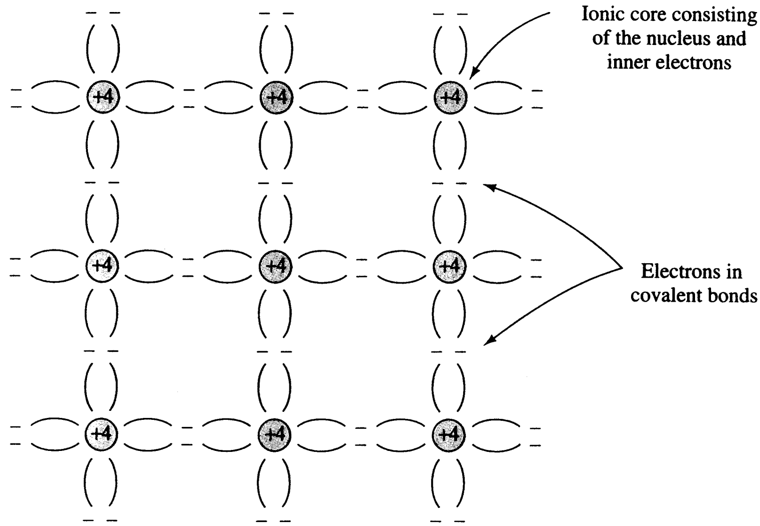


Figure 3.36 Intrinsic silicon crystal.

diagram shown in Figure 3.36. (In the actual crystal, the arrangement of the atoms is three dimensional—each atom is at the center of a tetrahedron with a neighbor located at each corner.)

At absolute zero temperature, electrons take the lowest energy states available. Thus, all of the valence electrons are bound in covalent bonds and are not free to move through the crystal. In this condition, silicon is an electrical insulator. However, at "room temperature" (approximately 300 K), a small fraction of the electrons gain sufficient thermal energy to break loose from their bonds. These **free electrons** can easily move through the crystal. This situation is illustrated in Figure 3.37.

If voltage is applied to intrinsic silicon, current flows. However, the number of free electrons is relatively small compared with that found in a good conductor. Thus, intrinsic silicon is classed as a **semiconductor**. Silicon contains about 5×10^{22} atoms/cm^3. At

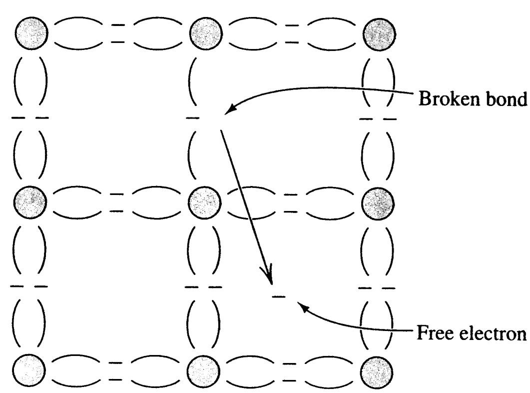


Figure 3.37 Thermal energy can break a bond, creating a vacancy and a free electron, both of which can move freely through the crystal.

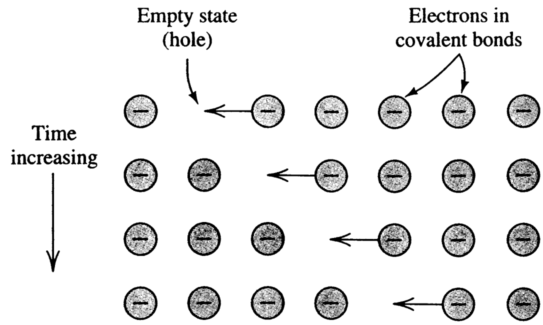


Figure 3.38 As electrons move to the left to fill a hole, the hole moves to the right.

room temperature, there are $n_i \cong 1.45 \times 10^{10}$ free electrons per cm^3. Thus, only about one valence electron in 1.4×10^{13} has broken loose from its bond at room temperature.

Conduction by Holes

Free electrons are not the only means by which current flows in intrinsic silicon. A broken bond can be filled by an electron from a nearby bond, as is illustrated in Figure 3.38. Even though it is the bound electrons that actually move, it is helpful to focus on the vacancy, or **hole**. We can think of a hole as a positive charge carrier that is free to move through the crystal, whereas bound electrons can move only if a vacancy exists nearby.

We can think of a hole as a positive charge carrier that is free to move through the crystal...

In an intrinsic semiconductor, an equal number of holes and free electrons are available to move easily through the crystal. We denote the free-electron concentration as n_i and the hole concentration as p_i. Thus, we can write

$$n_i = p_i \tag{3.24}$$

for a pure material. When an electric field is applied to the crystal, both types of carriers contribute to the flow of current.

Generation and Recombination

Free electrons and holes are generated by thermal energy, which causes covalent bonds to break at a rate depending strongly on temperature. The higher the temperature, the higher the rate of **generation**. On the other hand, when a free electron encounters a hole, **recombination** can occur: The hole and free electron combine to form a filled covalent bond. As the concentration of holes and electrons builds up, recombination occurs more frequently. Thus, at a given temperature, an equilibrium exists at which the rate of recombination equals the rate of generation of charge carriers. As the temperature increases, this equilibrium pertains to ever larger concentrations of charge carriers.

A higher concentration of charge carriers results in an increased capability of the material to conduct electrical current. Thus, the conductivity of an intrinsic semiconductor increases with temperature.

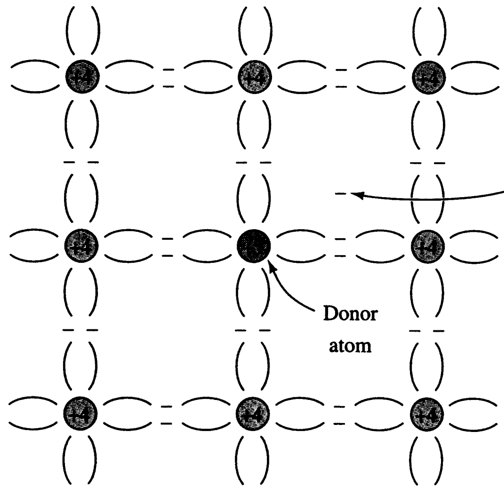


Figure 3.39 n-type silicon is created by adding valence five impurity atoms.

n-Type Semiconductor Material

Adding small amounts of suitable impurities to the crystal dramatically affects the relative concentration of holes and electrons. Then we have an **extrinsic** semiconductor. For example, if we add phosphorus, which has five valence electrons, the phosphorus atoms take positions in the crystal lattice and form covalent bonds with their four neighbors. The fifth valence electron is only weakly bound to the phosphorus atom.

At normal operating temperatures, this extra electron breaks its bond with the impurity atom and becomes a free electron. However, a hole is not created by the impurity atom—the positive charge that balances the free electron is locked in the **ionic core** of the impurity atom. Thus, we can create free electrons by adding pentavalent impurities known as **donors** to silicon. The resulting material is called ***n*-type** material. The crystal lattice of n-type silicon is depicted in Figure 3.39.

In n-type material, free electrons are called **majority carriers**, whereas holes are called **minority carriers**.

In n-type material, conduction is due mainly to the numerous free electrons. Thus, free electrons are called **majority carriers**, whereas holes are called **minority carriers**.

At normal operating temperatures, nearly all of the donor atoms give up their fifth electron. We say that the donors have become **ionized.** Positive charge is associated with each ionized donor atom. Of course, the net charge concentration in the material is zero. The positive charge of the ionized donors (and holes) is balanced by the negative charge of free electrons. Thus, we can equate the concentration of free electrons to the sum of the hole and donor concentrations; that is,

$$n = p + N_D \tag{3.25}$$

where N_D represents the concentration of donor atoms.

The Mass-Action Law

Not only is the free-electron concentration increased by the addition of donor atoms; the hole concentration is reduced, because the increased electron concentration makes hole recombination more likely. It turns out that the product of the hole concentration and the free-electron concentration is constant (for a given temperature). This is known as the **mass-action law**,

$$pn = p_i n_i \tag{3.26}$$

where p_i is the hole concentration in intrinsic material and n_i is the electron concentration in intrinsic material. Because Equation (3.24) states that the hole and electron concentrations are equal in intrinsic material, we can write

$$pn = n_i^2 \tag{3.27}$$

Holes are continually generated by thermal energy. Each hole wanders through the material until it finally combines with a free electron. The **average lifetime** of the minority carriers is an important parameter in the switching behavior of diodes and other semiconductor devices. We denote the average lifetime of the holes in n-type material as τ_p.

p-Type Semiconductor Material

Adding a trivalent impurity such as boron to pure silicon produces ***p*-type material**. Each impurity atom occupies a position in the crystal lattice and forms covalent bonds with three of its nearest neighbors. The impurity atom does not have the fourth electron needed to complete the bond with its fourth neighbor. At usual operating temperatures, an electron from a nearby silicon atom moves in to fill the fourth bond of each impurity atom. This creates a hole moving freely through the crystal. However, the electron is bound to the ionized impurity atom. Thus, conduction in p-type material is due mainly to holes.

In p-type material, holes are called majority carriers and electrons are called minority carriers. Of course, this is the reverse of the terminology for n-type material.

In p-type material, holes are called majority carriers and electrons are called minority carriers.

Valence-three impurities are called **acceptors**, because they accept an extra electron. Negative charge is associated with each ionized acceptor atom—four bound electrons are present, but only enough positive charge is present in the ionic core to balance the charge of three electrons. The crystal lattice structure of p-type silicon is depicted in Figure 3.40.

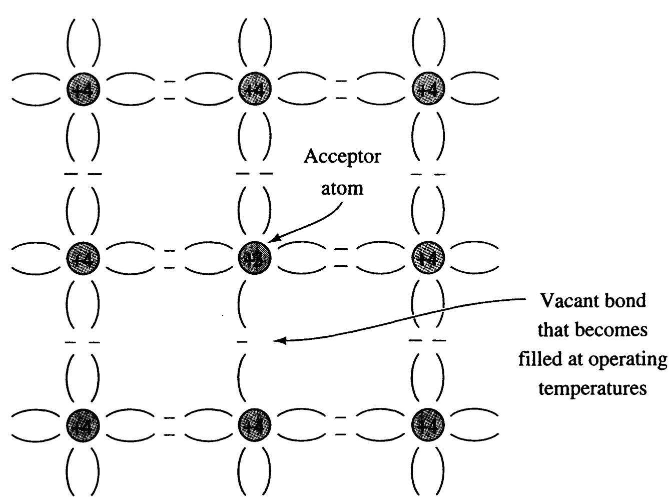


Figure 3.40 p-type silicon is created by adding valence three impurity atoms.

If we denote the concentration of acceptor atoms as N_A, we can write

$$N_A + n = p \tag{3.28}$$

because the net charge concentration in the material must be zero. The negative charge of the ionized acceptor atoms plus that of the free electrons equals the positive charge of the holes.

Cycling the Type of the Material

In fabricating integrated circuits, it is necessary to add impurities in stages, as discussed in Section 1.3. For example, we may start with n-type material, part of which we wish to change to p-type. This is accomplished by adding acceptors. When the acceptor concentration exceeds the original donor concentration, the material becomes p-type. Later, more donors can be added to part of the p region to change it back to n-type. For materials with both types of impurities, we have

$$p + N_D = n + N_A \tag{3.29}$$

Example 3.6 Calculation of Hole and Free-Electron Concentrations

Often we state units such as atoms/cm^3 (or electrons/cm^3) simply as cm^{-3} because the number of atoms (or electrons) is a pure number without units.

Suppose that we have silicon with $N_A = 10^{13}$ atoms/cm^3 and $N_D = 2 \times 10^{13}$ atoms/cm^3. The intrinsic electron concentration of silicon at room temperature (300 K) is 1.45×10^{10} cm^{-3}. Find the approximate hole and electron concentration for this doped material.

SOLUTION Because the donor concentration is greater than the acceptor concentration, we have n-type material. Thus, we anticipate that n is greater than n_i, and that p is less than n_i. Rearranging Equation (3.29), we obtain

$$n = p + N_D - N_A$$

Substituting values into this equation, we have

$$n = p + 10^{13}$$

Since $p < n_i = 1.45 \times 10^{10}\ \text{cm}^{-3}$, we conclude that

$$n \cong N_D - N_A = 10^{13}\ \text{cm}^{-3}$$

Now we use the mass-action law given in Equation (3.27), to get

$$np = n_i^2$$

Solving for p and substituting, we find that

$$p = 2.1 \times 10^7\ \text{cm}^{-3}$$

Notice that the free-electron concentration is about six orders of magnitude greater than the hole concentration in this material.

❑

Drift

Charge carriers move about randomly in the crystal due to thermal agitation. Collisions with the lattice cause the charge carriers to change direction frequently. The direction of travel after a collision is random. Consequently, with no applied electric field, the average velocity of the charge carriers in any particular direction is zero.

If an electric field is applied, force is exerted on the free charge carriers. (For holes, the force is in the same direction as the electric field, whereas for electrons, the force is opposite to the field.) Between collisions, the charge carriers are accelerated in the direction of the force. When the carriers collide with the lattice, their direction of travel becomes random again. Thus, the charge carriers do not keep accelerating. The net result is a constant average velocity in the direction of the force.

The average motion of the charge carriers due to an applied electric field is called **drift**. The average drift velocity is proportional to the electric field vector $\mathcal{E}$. We denote the drift velocity vector of electrons as $\mathbf{V}_n$ and the hole velocity vector as $\mathbf{V}_p$. Thus, we can write

$$\mathbf{V}_n = -\mu_n \mathcal{E} \tag{3.30}$$

in which the constant of proportionality μ_n is called the **mobility** of the free electrons. Because of the minus sign, the direction of the drift velocity is opposite that of the electric field.

Similarly, for holes, we have

$$\mathbf{V}_p = \mu_p \mathcal{E} \tag{3.31}$$

For silicon at 300 K, the approximate electron mobility is $\mu_n = 1500\,\text{cm}^2/(\text{Vs})$, whereas for holes it is $\mu_p = 475\,\text{cm}^2/(\text{Vs})$. (These values are approximate—the exact values depend on the concentrations of impurities and defects in the crystal.)

For a given applied field, electrons move about three times faster than holes in silicon. Later, we will see that transistors can be fabricated such that the current is mainly carried either by holes or by electrons. For fast digital circuits and high-frequency analog circuits, devices in which conduction is due to electrons are preferable to devices in which conduction is due to holes.

For fast digital circuits and high-frequency analog circuits, devices in which conduction is due to electrons are preferable to devices in which conduction is due to holes.

Diffusion

We will see that several mechanisms can create a higher-than-normal concentration of holes or electrons in a particular region of a semiconductor crystal. Because of their random thermal velocity, a concentration of charge carriers tends to spread out with time. This causes a flow of current known as **diffusion current**. Unless some action keeps producing excess charge carriers in a particular region of the crystal, the carrier concentration tends to become uniform and diffusion current ceases.

The Shockley–Haynes Experiment

Diffusion, recombination, and drift can be demonstrated by the Shockley–Haynes experiment. In this experiment, an excess of minority charge carriers is observed in an extrinsic semiconductor. For example, consider the bar of n-type material shown in Figure 3.41a. At $t = 0$, an intense flash of light illuminates a narrow region of the bar. The light causes

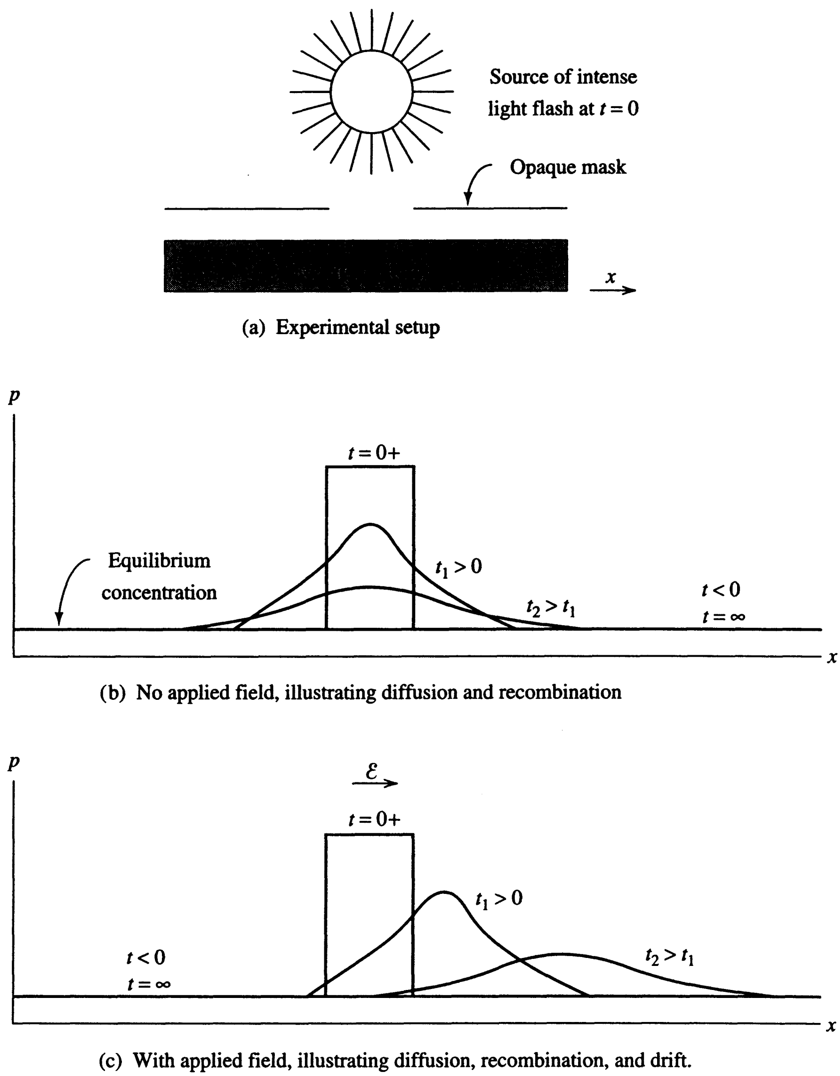


Figure 3.41 Shockley-Haynes experiment.

covalent bonds to be broken and increases the hole concentration in the illuminated portion of the bar. Figure 3.41b shows the plot of hole concentration versus x for $t = 0+$ (i.e., immediately after the flash at $t = 0$). With time, the concentration of holes spreads out due to diffusion.

Of course, the excess holes tend to recombine in addition to spreading by diffusion. Thus, the hole concentration eventually returns to its equilibrium value. The interval required for this to take place depends on the hole lifetime, τ_p.

If an external electric field is applied to the crystal, the carriers also move due to drift. (See Figure 3.41c.)

In this section, we have discussed conduction in semiconductors. Recombination, drift, and diffusion of charge carriers are important concepts in understanding device behavior. In the next section, we apply these concepts to the *pn* junction.

EXERCISE

3.18 Doped silicon contains 10^{16} donor atoms/cm^3. Find the free-electron concentration and the hole concentration.

Answer $n \cong 10^{16}$ electrons/cm^3, $p \cong 2.1 \times 10^4$ holes/cm^3.

3.10 PHYSICS OF THE JUNCTION DIODE

The Unbiased *pn* Junction

A *pn* junction consists of a single crystal of semiconductor material that is doped to produce *n*-type material on one side and *p*-type on the other side. The impurities can be added to the crystal as it is grown or added later, either by diffusion of impurity atoms into the crystal or by ion implantation. It is important for the crystal lattice to join the *n*-side to the *p*-side without disruption. This is possible only if the junction is grown as a single crystal. However, it is instructive to imagine the formation of a *pn* junction by joining a *p*-type crystal to an *n*-type crystal.

... it is instructive to imagine the formation of a *pn* junction by joining a *p*-type crystal to an *n*-type crystal.

Before the two halves of the junction are joined together, the *n* side contains a high concentration of free electrons and a low concentration of holes. The reverse condition exists in the *p*-type material. Immediately after the two types of material are joined, a concentration gradient exists across the junction for both types of carriers. (See Figure 3.42.)

Charge carriers diffuse whenever a concentration gradient exists (unless some force opposes the diffusion). Consequently, after the junction is formed, holes diffuse from the *p*-side to the *n*-side, and electrons diffuse in the opposite direction. This mutual diffusion

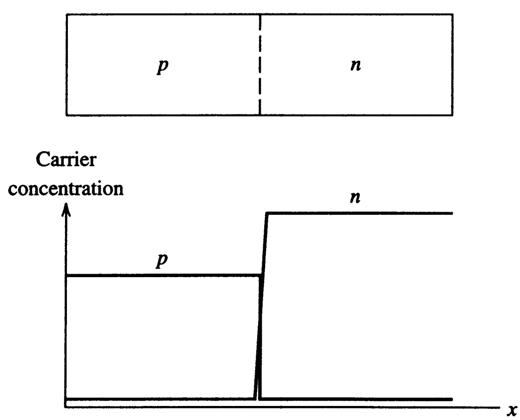


Figure 3.42 If a *pn* junction could be formed by joining a *p*-type crystal to an *n*-type crystal, a sharp gradient of hole concentration and electron concentration would exist at the junction immediately after joining the crystals.

the n-side increases, the hole concentration declines and the current is predominantly electron current. Similarly, far from the junction on the p-side, the current becomes predominantly hole current.

The device designer can control the fraction of the current crossing the junction due to electrons by appropriately selecting the doping levels on the two sides of the junction.

The device designer can control the fraction of the current crossing the junction due to electrons by appropriately selecting the doping levels on the two sides of the junction. For example, if the n-side is doped very heavily compared with the p-side, the current crossing the junction is due mostly to electrons. On the other hand, if the p-side is doped more heavily, the current at the junction is mostly hole current. This point will be important in Chapter 4, when we consider bipolar transistors.

3.11 SWITCHING AND HIGH-FREQUENCY BEHAVIOR

In many applications, ... diodes that can rapidly switch between the conducting and the nonconducting states are extremely desirable.

We have seen that the pn junction conducts little current when it is reverse biased and easily conducts large current when it is forward biased. In many applications, such as high-speed logic circuits and high-frequency rectifiers, diodes that can rapidly switch between the conducting and the nonconducting states are extremely desirable.

Unfortunately, the pn junction displays two charge-storage mechanisms that slow switching. Both of these mechanisms can be modeled as nonlinear capacitances. Before we consider charge storage in pn junctions, we briefly review conventional linear capacitors.

Review of Capacitance

A capacitor is constructed by separating two conducting plates by an insulator. (See Figure 3.46.) If voltage is applied to the capacitor terminals, charge flows in and collects on one plate. Meanwhile, current flows out of the other terminal, and a charge of opposite polarity collects on the other plate.

The magnitude of the net charge Q on one plate is proportional to the applied voltage V. Thus, we have

$$Q = CV \tag{3.33}$$

in which C is the capacitance.

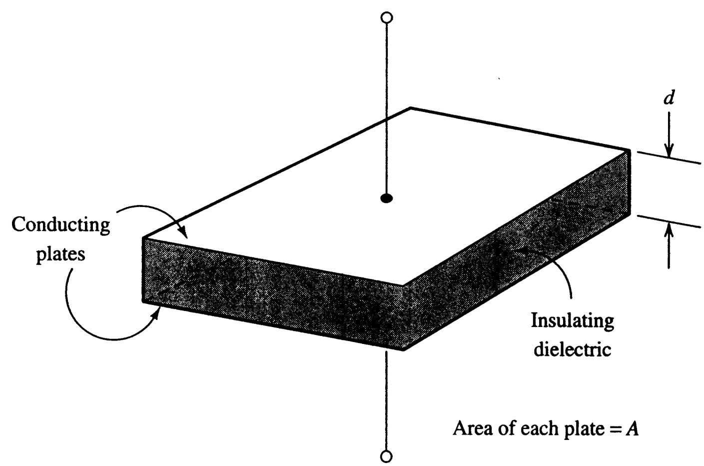


Figure 3.46 Parallel-plate capacitor.

For a parallel-plate capacitor, such as that shown in Figure 3.46, the capacitance is given by

$$C = \frac{\epsilon A}{d} \tag{3.34}$$

where A is the area of one plate, d is the distance between the plates, and ϵ is the **dielectric constant** of the material between the plates. Often, the dielectric constant is expressed as

$$\epsilon = \epsilon_r \epsilon_0 \tag{3.35}$$

where ϵ_r is the **relative dielectric constant** and $\epsilon_0 \cong 8.85 \times 10^{-12}$ F/m is the dielectric constant for a vacuum. [Actually, Equation (3.34) is an approximation that is accurate only if d is much smaller than the width and the length of the plates.]

Notice especially that the capacitance of the parallel-plate capacitor is proportional to the area of the plates and inversely proportional to the distance between the plates.

Depletion Capacitance

Consider the *pn* junction under reverse bias. As the magnitude of the voltage applied to the junction is increased, the field in the depletion region becomes stronger and the majority carriers are pulled back farther from the junction. This is illustrated in Figure 3.47.

The charge in the depletion region is similar to the charge stored on a parallel-plate capacitor. Unlike the situation with the parallel-plate capacitor, however, each additional increment of charge stored in the depletion region is separated by a larger distance. Thus,

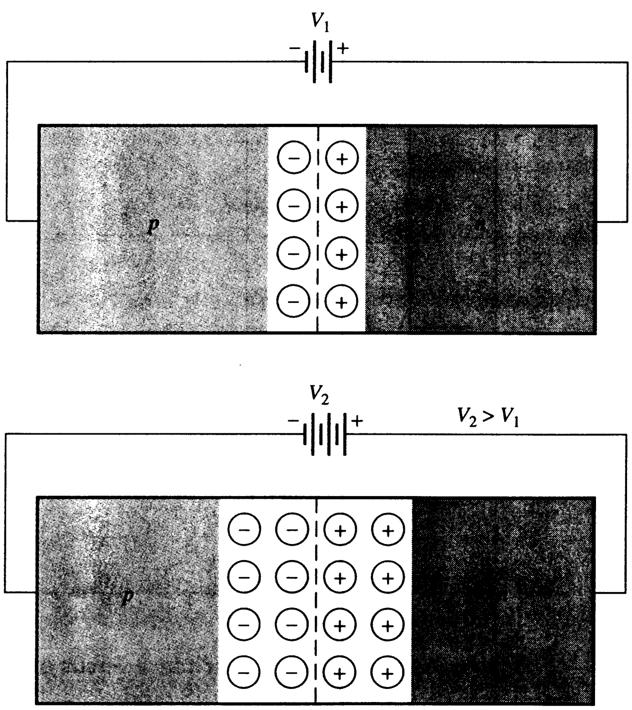


Figure 3.47 As the reverse bias voltage becomes greater, the charge stored in the depletion region increases.

the reverse-biased junction behaves as a capacitor, but the **depletion capacitance** is not constant. In other words, the stored charge is not directly proportional to the applied voltage. Because the relationship between the stored charge and the applied voltage is not linear, we say that the depletion capacitance is nonlinear.

For this nonlinear depletion capacitance, we define the incremental capacitance as

$$C_j = \left| \frac{dQ}{dv_D} \right| \tag{3.36}$$

in which dQ is the differential of the charge stored on one side of the depletion region and dv_D is the differential voltage. (This is similar to the concept of the dynamic resistance of a diode discussed in Section 3.8.) C_j is the capacitance of the diode for a small ac signal superimposed on a dc Q-point.

The incremental depletion capacitance is

Key equation for incremental (small-signal) depletion capacitance.

$$C_j = \frac{C_{j0}}{[1 - (V_{DQ}/\phi_0)]^m}, \tag{3.37}$$

in which C_{j0} is the incremental depletion capacitance for zero bias, V_{DQ} is the operating-point (Q-point) voltage (which is negative for reverse bias), ϕ_0 is the built-in barrier potential (typically about one volt), and m is called the grading coefficient. The value of m depends on how the doping changes with distance across the junction. For a linear change in doping across the junction, $m = 1/3$, and for an abrupt junction, $m = 1/2$.

For the 1N4148 small-signal switching diode, approximate values of these parameters are $C_{j0} = 2\text{ pF}$, $m = 1/2$, and $\phi_0 = 1$. A plot of the depletion capacitance versus bias voltage using these parameters is illustrated in Figure 3.48.

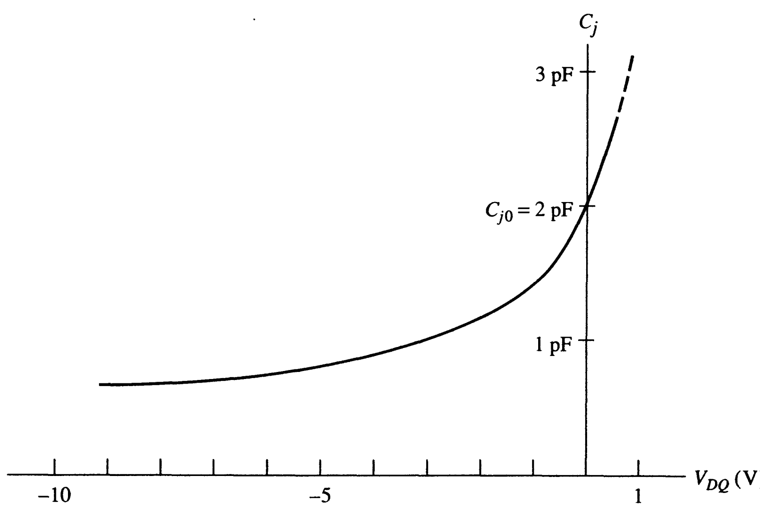


Figure 3.48 Depletion capacitance versus bias voltage for the 1N4148 diode.

The zero-bias depletion capacitance C_{j0} is approximately proportional to the area of the junction. Thus, it is larger for high-power rectifiers, which must be physically large to accommodate high power dissipation.

The value of C_{j0} also depends on the doping levels. In highly doped junctions, a large amount of charge can be stored close to the junction—as in a parallel-plate capacitor with a small plate separation. Thus, C_{j0} is relatively large for highly doped junctions and small for lightly doped junctions.

Diffusion Capacitance

Another basic charge-storage mechanism occurs when the *pn* junction is forward biased. To simplify our discussion, we consider an abrupt junction with much heavier doping on the p-side than on the n-side. (i.e., $N_A \gg N_D$) Sometimes this is called a p^+n junction, where p^+ refers to heavy doping of the p-material. For such a diode under forward bias, the current crossing the junction is due mainly to holes crossing from the p-side to the n-side.

Consider the hole concentration of the forward-biased p^+n junction shown in Figure 3.49. The charge associated with the holes that have crossed the junction is stored charge and is represented by the shaded areas in the figure. As the forward current is

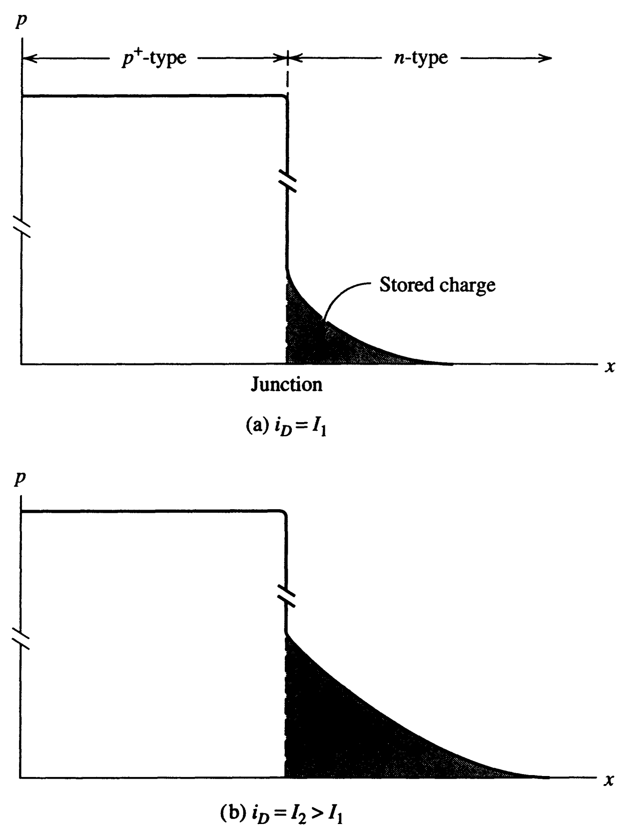


Figure 3.49 Hole concentration versus distance for two values of forward current.

increased, more holes cross the junction and the stored charge increases. Because this charge is associated with the holes that are diffusing into the n-side of the junction, we call the effect **diffusion capacitance**.

The incremental diffusion capacitance is given approximately by

$$C_{\text{dif}} = \frac{\tau_T I_{DQ}}{V_T} \tag{3.38}$$

in which τ_T is a parameter known as the **transit time** of the minority carriers. For the p^+n junction, $\tau_T = \tau_p$ is the lifetime of the holes on the n-side of the junction. On the other hand, for a pn^+ junction, we have $\tau_T = \tau_n$, which is the lifetime of the free electrons on the p-side. For a junction with comparable doping levels, τ_T is a weighted average of both lifetimes. Finally, I_{DQ} is the Q-point diode current, and as before, $V_T = kT/q$.

Complete Small-Signal Diode Model

A small-signal equivalent circuit for the pn-junction diode under forward bias is shown in Figure 3.50a. The resistance R_s represents the ohmic resistance of the bulk material on both sides of the junction. r_d is the dynamic resistance of the pn junction discussed in Section 3.8, where we saw that

$$r_d = \frac{nV_T}{I_{DQ}}$$

Furthermore, C_j is the depletion capacitance, and C_{dif} is the diffusion capacitance.

All of the equivalent circuit parameters, except for R_s, depend on the bias point. Under reverse-bias conditions, C_{dif} is zero, and r_d is an open circuit. Hence, the equivalent circuit simplifies as shown in Figure 3.50b.

This equivalent circuit is valid for the pn-junction diode over a wide range of frequencies, provided that small-signal conditions apply. However, diodes are most often used with large signals, and their nonlinear behavior must be taken into account. We illustrate this with a few examples.

Large-Signal Switching Behavior

Consider the circuit displayed in Figure 3.51. The waveform of the source voltage v_s is illustrated in Figure 3.52a. Until $t = 10$ ns, v_s is $+50$ V, and the diode is forward biased. At $t = 10$ ns, the source voltage switches rapidly to -50 V, reverse biasing the diode.

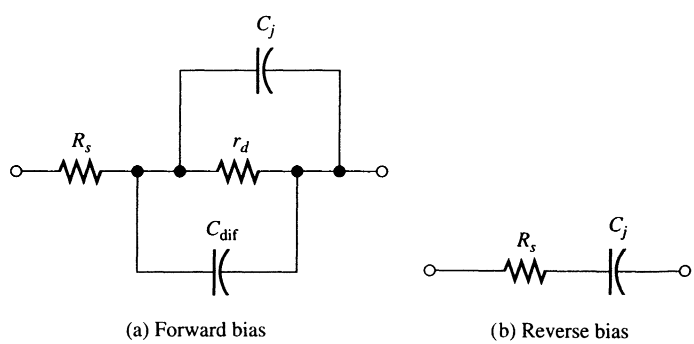


Figure 3.50 Small-signal linear circuits for the pn-junction diode.

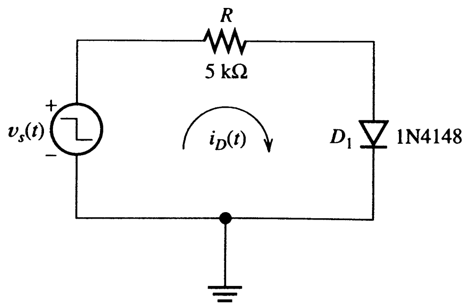


Figure 3.51 Circuit illustrating switching behavior of a *pn*-junction diode.

The resulting diode current is shown in Figure 3.52b. As we might expect, the diode current is approximately $50\,\text{V}/5\,\text{k}\Omega = +10\,\text{mA}$ until $t = 10$ ns. Then the source voltage jumps to $-50\,\text{V}$. Instead of dropping immediately to zero, the diode current reverses to $I_R \cong -10\,\text{mA}$. At approximately $t = 18\,\text{ns}$, the current begins to fall in magnitude and approaches zero at $t = 25\,\text{ns}$. In the interval immediately after the source reverses polarity, the diode continues to act as if it were forward biased. This is called the **storage interval** t_s, as labeled in Figure 3.52b.

We can explain the behavior of the diode as follows. (To simplify the discussion, we assume a diode that is heavily doped on the p-side compared with the n-side.) When forward bias is applied, holes flow across the junction into the n-side. These holes are minority carriers that diffuse into the n-side and eventually combine with free electrons. When v_s reverses polarity, the holes stored on the n-side can again cross the junction to the p-side. Until the supply of excess holes on the n-side is exhausted, the current flows easily in the reverse direction. This explains the storage interval of the diode-current waveform.

The storage interval for a pn-junction diode is given by

$$t_s = \tau_T \ln\left(\frac{I_F - I_R}{-I_R}\right) \tag{3.39}$$

in which τ_T is the transit time of the minority carriers. I_F is the forward current before switching, and I_R is the reverse current during the storage interval. Notice that the current is referenced in the forward direction, and I_R assumes a negative value.

After the excess holes have all recrossed the junction (or combined with free electrons on the n-side), the depletion capacitance of the diode is charged through the resistor. Thus, after the storage interval, we see an approximate exponential transient for the current in Figure 3.52b. (Since the depletion capacitance is nonlinear, the transient is not precisely exponential, as the transient is in a linear RC circuit.) The interval for this transient is called the **transition time** and is denoted by t_t. (By definition, the end of the transition interval occurs when the reverse diode current has reached a specified value, typically $I_R/10$.)

The total time interval for the diode to become an approximate open circuit is called the **reverse recovery time** and is denoted by t_{rr}. The reverse recovery time is the sum of the storage time and the transition time:

$$t_{rr} = t_s + t_t \tag{3.40}$$

The transition time t_t depends on the circuit resistance. (Recall the concept of the RC time constant for a linear circuit.) Even though the depletion capacitance is not linear, the transition time is proportional to the circuit resistance.

Data sheets for diodes often give storage times and reverse recovery times for a specified forward current I_F, reverse current I_R, and circuit resistance. Usually, the test circuits for these specifications are shown on the data sheet.

The diode voltage is illustrated in Figure 3.52c. In order to be able to see the details of the diode voltage during forward bias, 100 times the diode voltage is also plotted. Notice that the diode voltage remains positive during the storage time, showing that the diode continues to act as if it were forward biased, even though the current has reversed direction.

The terminal voltage of the diode does fall somewhat when the current reverses, because the voltage drop across the ohmic resistance R_s of the diode reverses polarity. Prior to $t = 10$ ns, the terminal voltage is the sum of the junction voltage and the ohmic

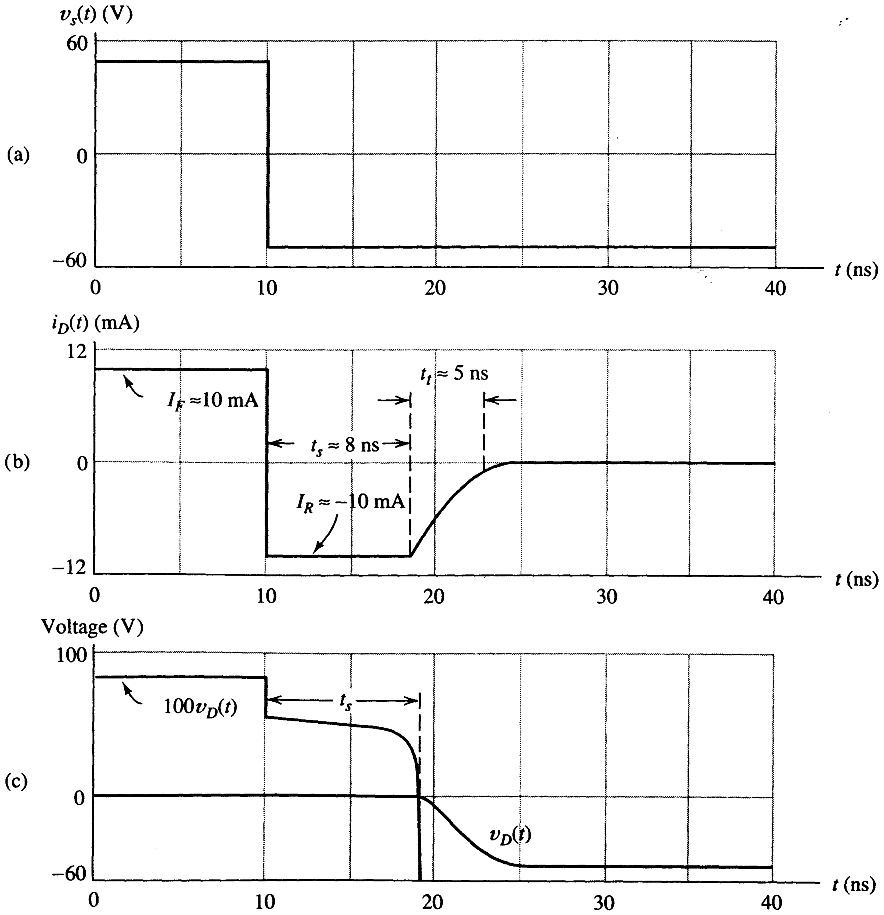


Figure 3.52 Waveforms for the circuit of Figure 3.51.

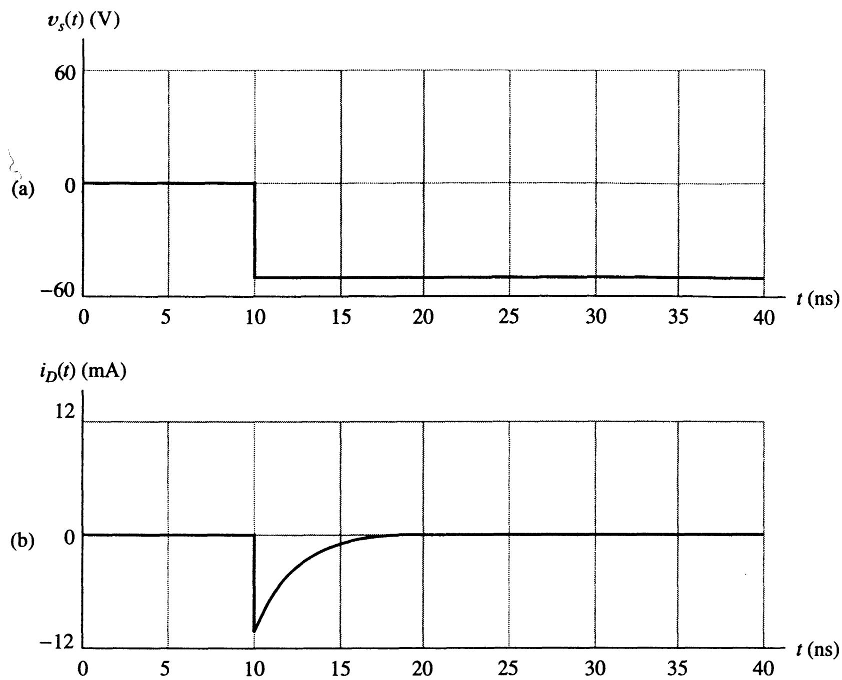


Figure 3.53 Another set of waveforms for the circuit of Figure 3.51. Notice the absence of a storage interval.

drop. On the other hand, between $t = 10\,\text{ns}$ and $t = 18\,\text{ns}$, the terminal voltage is the junction voltage minus the ohmic drop.

It is instructive to consider another source voltage waveform for the circuit of Figure 3.51. For example, Figure 3.53a shows a source voltage that is zero until $t = 10\,\text{ns}$. Then it switches to $-50\,\text{V}$. The corresponding diode current is illustrated in Figure 3.53b. In this case, because the diode current is zero prior to $t = 10\,\text{ns}$, there is no excess hole concentration on the n-side of the junction. Therefore, there is no storage interval. The diode immediately enters the transition phase, and it switches to an open circuit much more quickly if the forward current is zero before switching.

EXERCISE

3.19 Consider the parallel-plate capacitor shown in Figure 3.46. The plates have dimensions of $20\,\mu\text{m} \times 30\,\mu\text{m}$. The relative dielectric constant of the material between the plates is $\epsilon_r = 11.9$ (the value for silicon). The capacitance is 1 pF, a typical zero-bias depletion capacitance for a discrete small-signal diode. Find the distance between the plates. (The answer is the approximate zero-bias thickness of the depletion region.)

Answer $d = 6.32 \times 10^{-8}\,\text{m}$.

EXERCISE

3.20 A certain abrupt-junction diode ($m = 1/2$) has a zero-bias depletion capacitance of $C_{j0} = 5\,\text{pF}$ and a built-in barrier potential of $\phi_0 = 0.8\,\text{V}$. (a) Compute the depletion capacitance for a reverse-bias voltage of 5 V. (b) Do the same for a reverse-bias voltage of 50 V.

Answer (a) $C_j = 1.86\,\text{pF}$; (b) $C_j = 0.627\,\text{pF}$.

EXERCISE

3.21 A certain diode has a transit time of 10 ns. Find values for the small-signal equivalent circuit parameters r_d and C_{dif} at $I_{DQ} = 5\,\text{mA}$. Assume an emission coefficient of $n = 1$ and a temperature of 300 K.

Answer $r_d = 5.2\,\Omega$ and $C_{\text{dif}} = 1920\,\text{pF}$.

3.12 COMPUTER-AIDED ANALYSIS OF DIODE CIRCUITS

In this section, we show several examples of how to use SPICE to analyze diode circuits.

Example 3.7 Plotting V–I Diode Characteristics with SPICE

Obtain a plot of the room-temperature volt–ampere characteristic of the 1N750 Zener diode for currents ranging from −10 mA to 10 mA. The 1N750 has a breakdown voltage of approximately 4.7 V. Repeat for temperatures of 0, 25, 50, 75, and 100°C.

The circuit file is named Fig3_54 and is found on the website.

SOLUTION First we start Schematics and draw a circuit containing a dc current source and a 1N750 diode. The resulting circuit is shown in Figure 3.54. Then

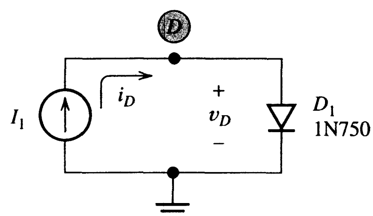


Figure 3.54 Circuit used to display the V-I characteristics of the 1N750 Zener diode.

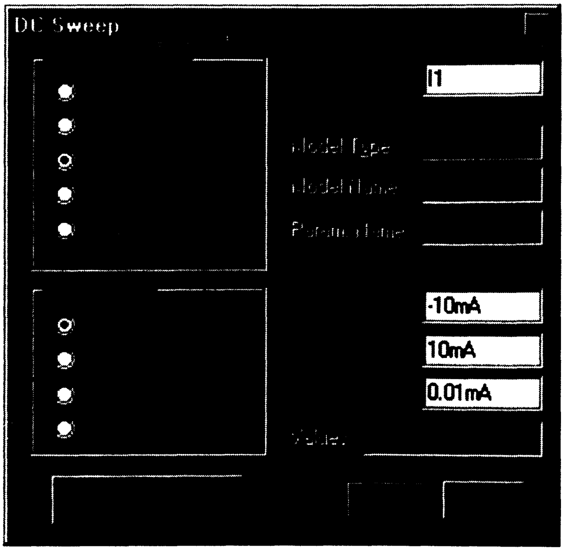


Figure 3.55 Dc-sweep-setup window.

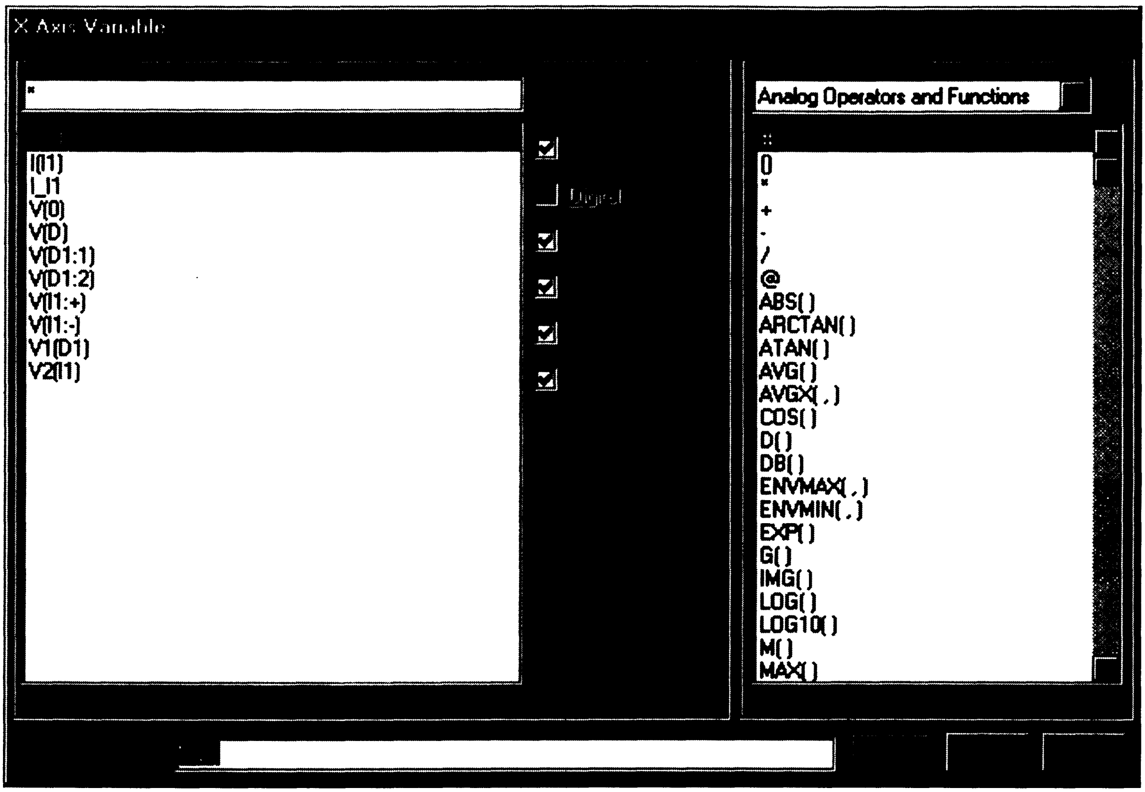


Figure 3.56 X-axis-variable window.

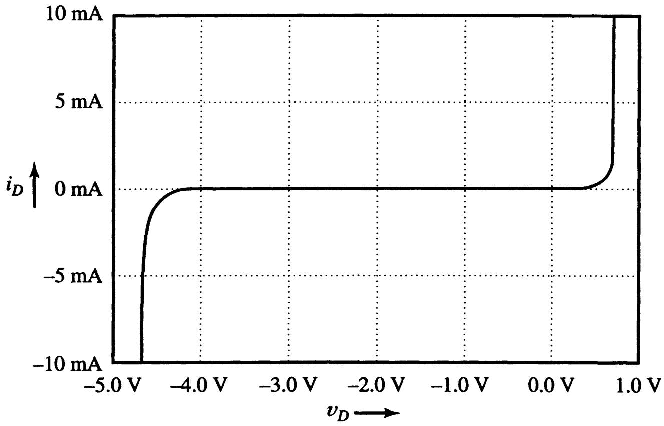


Figure 3.57 SPICE generated plot for the 1N750 Zener diode at 25°C.

we use the **analysis/setup/dc sweep** commands to bring up the window shown in Figure 3.55. In this window, we give the name of the dc source that we wish to vary and the range of current values. Notice that we have selected a linear sweep.

Next, we use the **analysis/simulate** command to start the simulation, after which Probe starts. Since we have swept the current source, Probe comes up with current on the x-axis. However, we want to plot the current on the y-axis and voltage on the x-axis. Thus, we use the **plot/x-axis/axis variable** commands to bring up the window shown in Figure 3.56. Then we choose V(D) as the variable. Next, we use the **trace/add** command and select I(D1) as the y-axis variable. This yields the plot displayed in Figure 3.57, which is typical of a Zener diode.

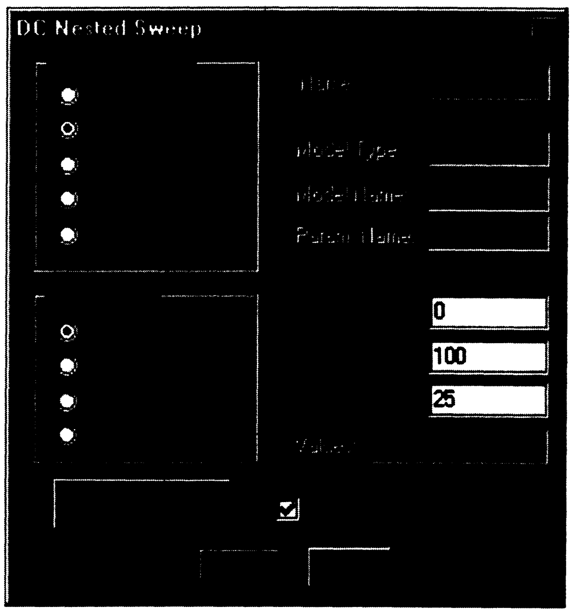


Figure 3.58 Dc-nested-sweep window.

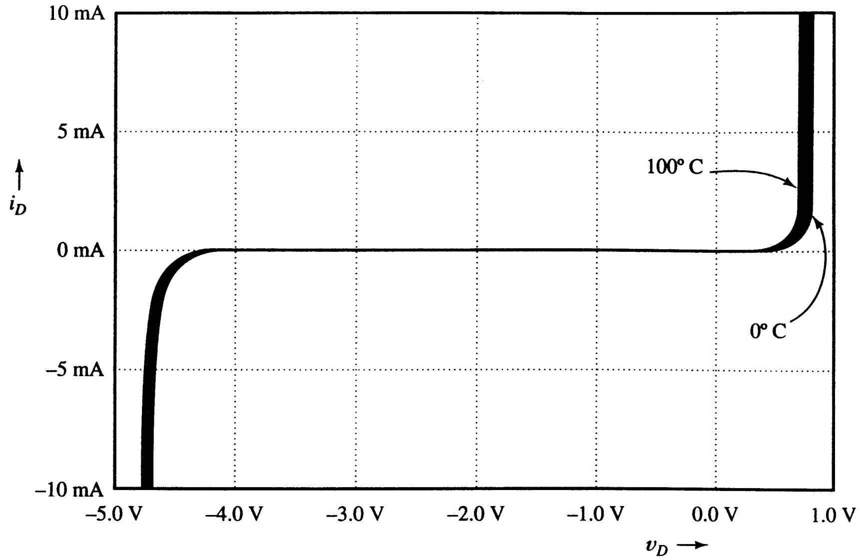


Figure 3.59 1N750 characteristics for temperature ranging from 0 to 100°C in 25° increments.

To obtain a family of plots for various temperatures, we return to Schematics and use the **analysis/setup/dc sweep/nested sweep** commands to bring up the window illustrated in Figure 3.58. We select temperature as the nested sweep variable, and we choose the linear sweep type and the desired range of temperatures. *Be sure to enable the nested sweep.* Then if we return to Schematics and use the **analysis/simulate** command, the circuit is simulated for each temperature and Probe comes up. As before, we change the x-axis variable to V(D) and select I(D1) as the trace. The family of plots is displayed in Figure 3.59.

❑

Example 3.8* Switching Behavior of the 1N4148 Diode

Use DesignLab to simulate the circuit of Figure 3.51. Compare your results with those shown in Figure 3.52.

SOLUTION First we use Schematics to draw the circuit (Figure 3.51). Then we double click the left button of the mouse on the voltage source symbol to bring up the window displayed in Figure 3.60. To set up the pulse waveform of Figure 3.52a, we need to specify the attributes as V1 = 50 V, V2 = −50 V, and TD = 10 ns. Next, we use the **analysis/setup/transient** command to bring up the

The circuit file is named Fig3_51 and can be found on the website.

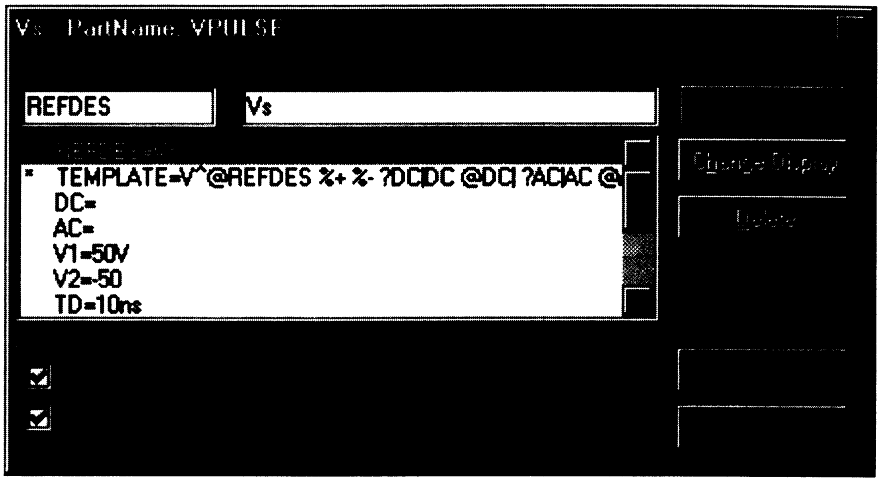


Figure 3.60 Window for the pulse source.

window illustrated in Figure 3.61. We select a final time of 40 ns and a step of 0.1 ns. After using the **analysis/simulate** command, Probes starts and we select I(D1) as the variable to plot. The resulting plot is identical to Figure 3.52b.

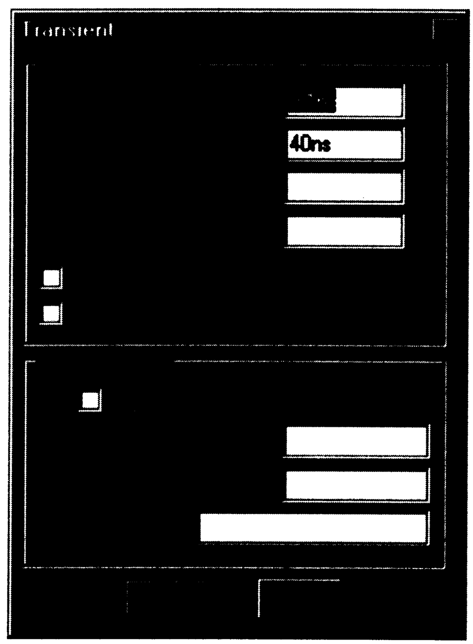


Figure 3.61 Transient setup window.

❑

Almost all of the circuits discussed in this book can be simulated by using DesignLab or similar software packages. Intelligent use of computer simulation can help you become an expert electronic-circuit designer. Select a circuit, think about how it works, then simulate it, and compare the results with your expectations. When the results agree, try a more complex circuit; when they don't, rethink your understanding of the circuit. After you have some experience with existing circuits, start designing your own.

Intelligent use of computer simulation can help you become an expert electronic-circuit designer.

EXERCISE

3.22 Use SPICE to obtain the volt–ampere characteristic of the 1N4148 diode.

EXERCISE

3.23 Use SPICE to simulate the circuit of Figure 3.51 for the source waveform shown in Figure 3.53a. Plot the diode current against time.

Answer The result should be very similar to Figure 3.53b. Some variation may occur depending on the diode model.

SUMMARY

- Diodes are two-terminal devices that conduct current easily in one direction, but not in the other.
- At room temperature, a small-signal silicon diode has a voltage of approximately 0.6 V when carrying current in the forward direction. As the temperature increases, the forward voltage decreases by about 2 mV/K. Under reverse bias, the current is very small, typically 1 nA. A rule of thumb is that the reverse current doubles for each 10-K increase in temperature. Eventually, if sufficient reverse voltage is applied, the diode enters the reverse-breakdown region.
- Diodes that are intended to operate in the breakdown region are called Zener diodes. Zener diodes are often used in applications for which a constant voltage in breakdown is desirable.
- Circuits containing a nonlinear device such as a diode can be analyzed using a graphical technique called a load-line analysis. The load-line equation is obtained by applying KVL or KCL. The equation plots as a straight line that can be drawn by locating two points.
- The ideal-diode model is a short circuit for forward currents and an open circuit for reverse voltages.