CHAPTER

Semiconductor Diodes

1

1.1 INTRODUCTION

It is now some 50 years since the first transistor was introduced on December 23, 1947. For those of us who experienced the change from glass envelope tubes to the solid-state era, it still seems like a few short years ago. The first edition of this text contained heavy coverage of tubes, with succeeding editions involving the important decision of how much coverage should be dedicated to tubes and how much to semiconductor devices. It no longer seems valid to mention tubes at all or to compare the advantages of one over the other—we are firmly in the solid-state era.

The miniaturization that has resulted leaves us to wonder about its limits. Complete systems now appear on wafers thousands of times smaller than the single element of earlier networks. New designs and systems surface weekly. The engineer becomes more and more limited in his or her knowledge of the broad range of advances—it is difficult enough simply to stay abreast of the changes in one area of research or development. We have also reached a point at which the primary purpose of the container is simply to provide some means of handling the device or system and to provide a mechanism for attachment to the remainder of the network. Miniaturization appears to be limited by three factors (each of which will be addressed in this text): the quality of the semiconductor material itself, the network design technique, and the limits of the manufacturing and processing equipment.

1.2 IDEAL DIODE

The first electronic device to be introduced is called the *diode.* It is the simplest of semiconductor devices but plays a very vital role in electronic systems, having characteristics that closely match those of a simple switch. It will appear in a range of applications, extending from the simple to the very complex. In addition to the details of its construction and characteristics, the very important data and graphs to be found on specification sheets will also be covered to ensure an understanding of the terminology employed and to demonstrate the wealth of information typically available from manufacturers.

The term *ideal* will be used frequently in this text as new devices are introduced. It refers to any device or system that has ideal characteristics—perfect in every way. It provides a basis for comparison, and it reveals where improvements can still be made. The *ideal diode* is a *two-terminal* device having the symbol and characteristics shown in Figs. 1.1a and b, respectively.

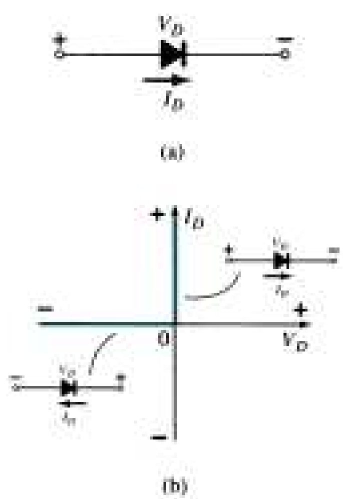


Figure 1.1 Ideal diode: (a) symbol; (b) characteristics.

Ideally, a diode will conduct current in the direction defined by the arrow in the symbol and act like an open circuit to any attempt to establish current in the opposite direction. In essence:

The characteristics of an ideal diode are those of a switch that can conduct current in only one direction.

In the description of the elements to follow, it is critical that the various *letter symbols*, *voltage polarities*, and *current directions* be defined. If the polarity of the applied voltage is consistent with that shown in Fig. 1.1a, the portion of the characteristics to be considered in Fig. 1.1b is to the right of the vertical axis. If a reverse voltage is applied, the characteristics to the left are pertinent. If the current through the diode has the direction indicated in Fig. 1.1a, the portion of the characteristics to be considered is above the horizontal axis, while a reversal in direction would require the use of the characteristics below the axis. For the majority of the device characteristics that appear in this book, the *ordinate* (or "y" axis) will be the *current* axis, while the *abscissa* (or "x" axis) will be the *voltage* axis.

One of the important parameters for the diode is the resistance at the point or region of operation. If we consider the conduction region defined by the direction of I_D and polarity of V_D in Fig. 1.1a (upper-right quadrant of Fig. 1.1b), we will find that the value of the forward resistance, R_F, as defined by Ohm's law is

$$R_F = \frac{V_F}{I_F} = \frac{0 \text{ V}}{2, 3, \text{mA}, \ldots, \text{ or any positive value}} = \mathbf{0\ \Omega} \quad \text{(short circuit)}$$

where V_F is the forward voltage across the diode and I_F is the forward current through the diode.

The ideal diode, therefore, is a short circuit for the region of conduction.

Consider the region of negatively applied potential (third quadrant) of Fig. 1.1b,

$$R_R = \frac{V_R}{I_R} = \frac{-5, -20, \text{ or any reverse-bias potential}}{0 \text{ mA}} = \boldsymbol{\infty\ \Omega} \quad \text{(open-circuit)}$$

where V_R is reverse voltage across the diode and I_R is reverse current in the diode.

The ideal diode, therefore, is an open circuit in the region of nonconduction.

In review, the conditions depicted in Fig. 1.2 are applicable.

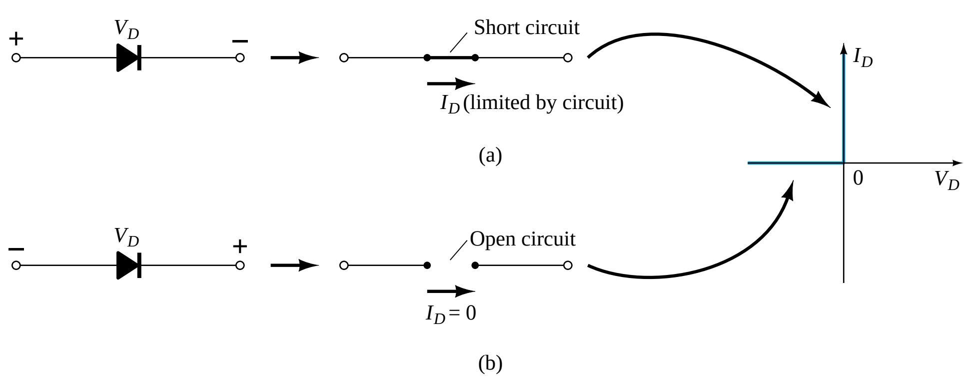


Figure 1.2 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the applied bias.

In general, it is relatively simple to determine whether a diode is in the region of conduction or nonconduction simply by noting the direction of the current I_D established by an applied voltage. For conventional flow (opposite to that of electron flow), if the resultant diode current has the same direction as the arrowhead of the diode symbol, the diode is operating in the conducting region as depicted in Fig. 1.3a. If the resulting current has the opposite direction, as shown in Fig. 1.3b, the open-circuit equivalent is appropriate.

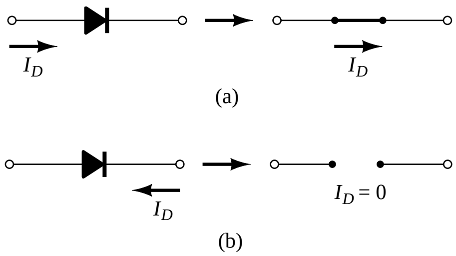


Figure 1.3 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the direction of conventional current established by the network.

As indicated earlier, the primary purpose of this section is to introduce the characteristics of an ideal device for comparison with the characteristics of the commercial variety. As we progress through the next few sections, keep the following questions in mind:

How close will the forward or "on" resistance of a practical diode compare with the desired 0-Ω level?

Is the reverse-bias resistance sufficiently large to permit an open-circuit approximation?

1.3 SEMICONDUCTOR MATERIALS

The label *semiconductor* itself provides a hint as to its characteristics. The prefix *semi-* is normally applied to a range of levels midway between two limits.

The term conductor is applied to any material that will support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals.

An insulator is a material that offers a very low level of conductivity under pressure from an applied voltage source.

A semiconductor, therefore, is a material that has a conductivity level somewhere between the extremes of an insulator and a conductor.

Inversely related to the conductivity of a material is its resistance to the flow of charge, or current. That is, the higher the conductivity level, the lower the resistance level. In tables, the term *resistivity* (ρ, Greek letter rho) is often used when comparing the resistance levels of materials. In metric units, the resistivity of a material is measured in Ω-cm or Ω-m. The units of Ω-cm are derived from the substitution of the units for each quantity of Fig. 1.4 into the following equation (derived from the basic resistance equation $R = \rho l/A$):

$$\rho = \frac{RA}{l} = \frac{(\Omega)(\text{cm}^2)}{\text{cm}} \Rightarrow \Omega\text{-cm} \tag{1.1}$$

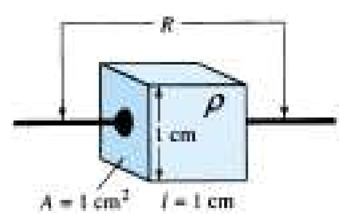


Figure 1.4 Defining the metric units of resistivity.

In fact, if the area of Fig. 1.4 is 1 cm^2 and the length 1 cm, the magnitude of the resistance of the cube of Fig. 1.4 is equal to the magnitude of the resistivity of the material as demonstrated below:

$$|R| = \rho \frac{l}{A} = \rho \frac{(1\text{ cm})}{(1\text{ cm}^2)} = |\rho|\text{ohms}$$

This fact will be helpful to remember as we compare resistivity levels in the discussions to follow.

In Table 1.1, typical resistivity values are provided for three broad categories of materials. Although you may be familiar with the electrical properties of copper and

TABLE 1.1 Typical Resistivity Values

Conductor	*Semiconductor*	*Insulator*
$\rho \cong 10^{-6}\ \Omega$-cm (copper)	$\rho \cong 50\ \Omega$-cm (germanium) $\rho \cong 50 \times 10^3\ \Omega$-cm (silicon)	$\rho \cong 10^{12}\ \Omega$-cm (mica)

mica from your past studies, the characteristics of the semiconductor materials of germanium (Ge) and silicon (Si) may be relatively new. As you will find in the chapters to follow, they are certainly not the only two semiconductor materials. They are, however, the two materials that have received the broadest range of interest in the development of semiconductor devices. In recent years the shift has been steadily toward silicon and away from germanium, but germanium is still in modest production.

Note in Table 1.1 the extreme range between the conductor and insulating materials for the 1-cm length (1-cm^2 area) of the material. Eighteen places separate the placement of the decimal point for one number from the other. Ge and Si have received the attention they have for a number of reasons. One very important consideration is the fact that they can be manufactured to a very high purity level. In fact, recent advances have reduced impurity levels in the pure material to 1 part in 10 billion (1:10,000,000,000). One might ask if these low impurity levels are really necessary. They certainly are if you consider that the addition of one part impurity (of the proper type) per million in a wafer of silicon material can change that material from a relatively poor conductor to a good conductor of electricity. We are obviously dealing with a whole new spectrum of comparison levels when we deal with the semiconductor medium. The ability to change the characteristics of the material significantly through this process, known as "doping," is yet another reason why Ge and Si have received such wide attention. Further reasons include the fact that their characteristics can be altered significantly through the application of heat or light—an important consideration in the development of heat- and light-sensitive devices.

Some of the unique qualities of Ge and Si noted above are due to their atomic structure. The atoms of both materials form a very definite pattern that is periodic in nature (i.e., continually repeats itself). One complete pattern is called a *crystal* and the periodic arrangement of the atoms a *lattice.* For Ge and Si the crystal has the three-dimensional diamond structure of Fig. 1.5. Any material composed solely of repeating crystal structures of the same kind is called a *single-crystal* structure. For semiconductor materials of practical application in the electronics field, this single-crystal feature exists, and, in addition, the periodicity of the structure does not change significantly with the addition of impurities in the doping process.

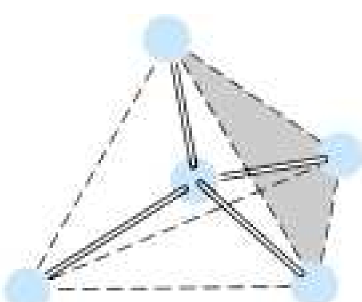


Figure 1.5 Ge and Si single-crystal structure.

Let us now examine the structure of the atom itself and note how it might affect the electrical characteristics of the material. As you are aware, the atom is composed of three basic particles: the *electron,* the *proton,* and the *neutron.* In the atomic lattice, the neutrons and protons form the *nucleus,* while the electrons revolve around the nucleus in a fixed *orbit.* The Bohr models of the two most commonly used semiconductors, *germanium* and *silicon,* are shown in Fig. 1.6.

As indicated by Fig. 1.6a, the germanium atom has 32 orbiting electrons, while silicon has 14 orbiting electrons. In each case, there are 4 electrons in the outermost (*valence*) shell. The potential (*ionization potential*) required to remove any one of these 4 valence electrons is lower than that required for any other electron in the structure. In a pure germanium or silicon crystal these 4 valence electrons are bonded to 4 adjoining atoms, as shown in Fig. 1.7 for silicon. Both Ge and Si are referred to as *tetravalent atoms* because they each have four valence electrons.

A bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding.

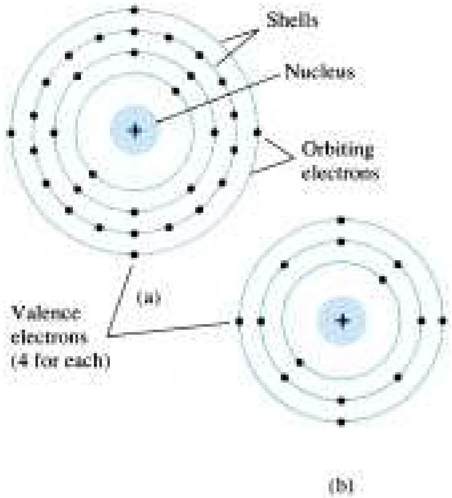


Figure 1.6 Atomic structure: (a) germanium; (b) silicon.

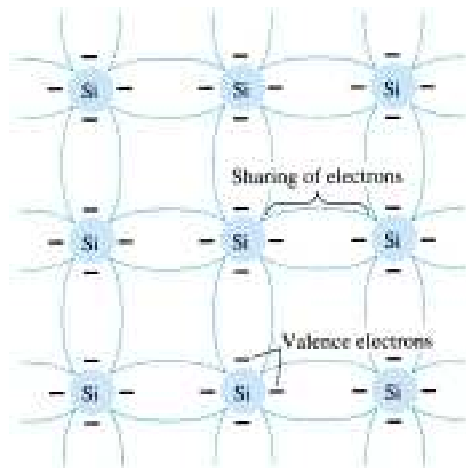


Figure 1.7 Covalent bonding of the silicon atom.

Although the covalent bond will result in a stronger bond between the valence electrons and their parent atom, it is still possible for the valence electrons to absorb sufficient kinetic energy from natural causes to break the covalent bond and assume the "free" state. The term *free* reveals that their motion is quite sensitive to applied electric fields such as established by voltage sources or any difference in potential. These natural causes include effects such as light energy in the form of photons and thermal energy from the surrounding medium. At room temperature there are approximately 1.5×10^{10} free carriers in a cubic centimeter of intrinsic silicon material.

Intrinsic materials are those semiconductors that have been carefully refined to reduce the impurities to a very low level—essentially as pure as can be made available through modern technology.

The free electrons in the material due only to natural causes are referred to as *intrinsic carriers.* At the same temperature, intrinsic germanium material will have approximately 2.5×10^{13} free carriers per cubic centimeter. The ratio of the number of carriers in germanium to that of silicon is greater than 10^3 and would indicate that germanium is a better conductor at room temperature. This may be true, but both are still considered poor conductors in the intrinsic state. Note in Table 1.1 that the resistivity also differs by a ratio of about 1000:1, with silicon having the larger value. This should be the case, of course, since resistivity and conductivity are inversely related.

An increase in temperature of a semiconductor can result in a substantial increase in the number of free electrons in the material.

As the temperature rises from absolute zero (0 K), an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and contribute to the number of free carriers as described above. This increased number of carriers will increase the conductivity index and result in a lower resistance level.

Semiconductor materials such as Ge and Si that show a reduction in resistance with increase in temperature are said to have a negative temperature coefficient.

You will probably recall that the resistance of most conductors will increase with temperature. This is due to the fact that the numbers of carriers in a conductor will not increase significantly with temperature, but their vibration pattern about a relatively fixed location will make it increasingly difficult for electrons to pass through. An increase in temperature therefore results in an increased resistance level and a *positive temperature coefficient.*

1.4 ENERGY LEVELS

In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron, as shown in Fig. 1.8a. Each material will, in fact, have its own set of permissible energy levels for the electrons in its atomic structure.

The more distant the electron from the nucleus, the higher the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

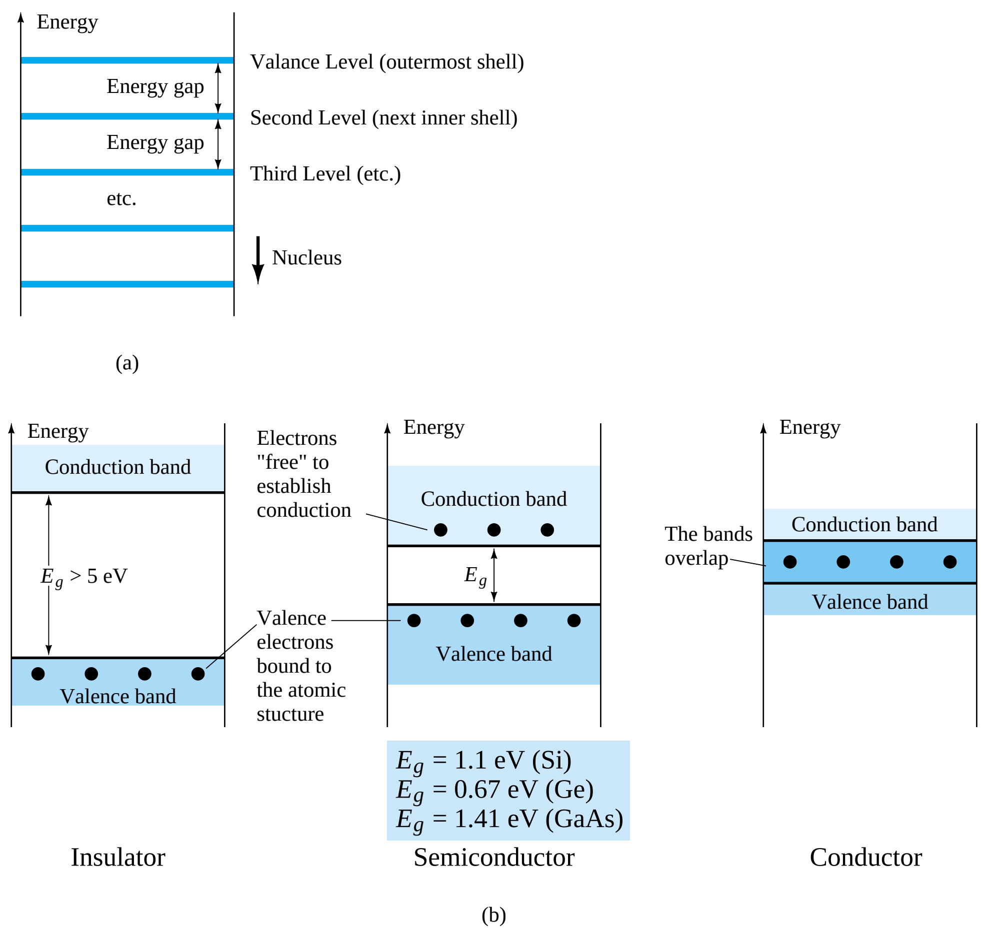


Figure 1.8 Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, semiconductor, and conductor.

Between the discrete energy levels are gaps in which no electrons in the isolated atomic structure can appear. As the atoms of a material are brought closer together to form the crystal lattice structure, there is an interaction between atoms that will result in the electrons in a particular orbit of one atom having slightly different energy levels from electrons in the same orbit of an adjoining atom. The net result is an expansion of the discrete levels of possible energy states for the valence electrons to that of bands as shown in Fig. 1.8b. Note that there are boundary levels and maximum energy states in which any electron in the atomic lattice can find itself, and there remains a *forbidden region* between the valence band and the ionization level. Recall that ionization is the mechanism whereby an electron can absorb sufficient energy to break away from the atomic structure and enter the conduction band. You will note that the energy associated with each electron is measured in *electron volts* (eV). The unit of measure is appropriate, since

$$W = QV \quad \text{eV} \tag{1.2}$$

as derived from the defining equation for voltage $V = W/Q$. The charge Q is the charge associated with a single electron.

Substituting the charge of an electron and a potential difference of 1 volt into Eq. (1.2) will result in an energy level referred to as one *electron volt.* Since energy is also measured in joules and the charge of one electron $= 1.6 \times 10^{-19}$ coulomb,

$$W = QV = (1.6 \times 10^{-19}\ \text{C})(1\ \text{V})$$

and

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J} \tag{1.3}$$

At 0 K or absolute zero (−273.15°C), all the valence electrons of semiconductor materials find themselves locked in their outermost shell of the atom with energy levels associated with the valence band of Fig. 1.8b. However, at room temperature (300 K, 25°C) a large number of valence electrons have acquired sufficient energy to leave the valence band, cross the energy gap defined by E_g in Fig. 1.8b and enter the conduction band. For silicon E_g is 1.1 eV, for germanium 0.67 eV, and for gallium arsenide 1.41 eV. The obviously lower E_g for germanium accounts for the increased number of carriers in that material as compared to silicon at room temperature. Note for the insulator that the energy gap is typically 5 eV or more, which severely limits the number of electrons that can enter the conduction band at room temperature. The conductor has electrons in the conduction band even at 0 K. Quite obviously, therefore, at room temperature there are more than enough free carriers to sustain a heavy flow of charge, or current.

We will find in Section 1.5 that if certain impurities are added to the intrinsic semiconductor materials, energy states in the forbidden bands will occur which will cause a net reduction in E_g for both semiconductor materials—consequently, increased carrier density in the conduction band at room temperature!

1.5 EXTRINSIC MATERIALS—*n*- AND *p*-TYPE

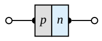
The characteristics of semiconductor materials can be altered significantly by the addition of certain impurity atoms into the relatively pure semiconductor material. These impurities, although only added to perhaps 1 part in 10 million, can alter the band structure sufficiently to totally change the electrical properties of the material.

A semiconductor material that has been subjected to the doping process is called an extrinsic material.

There are two extrinsic materials of immeasurable importance to semiconductor device fabrication: *n*-type and *p*-type. Each will be described in some detail in the following paragraphs.

n-Type Material

Both the *n*- and *p*-type materials are formed by adding a predetermined number of impurity atoms into a germanium or silicon base. The *n*-type is created by introducing those impurity elements that have *five* valence electrons (*pentavalent*), such as *antimony, arsenic,* and *phosphorus.* The effect of such impurity elements is indicated in



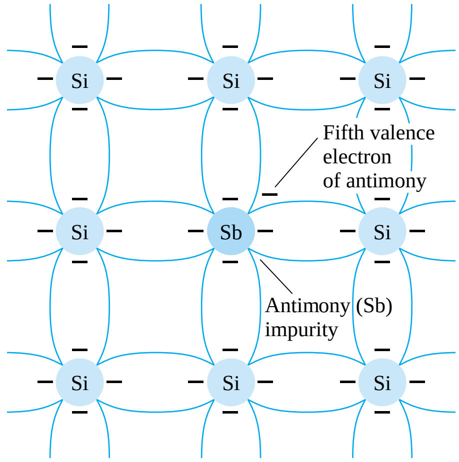


Figure 1.9 Antimony impurity in *n*-type material.

Fig. 1.9 (using antimony as the impurity in a silicon base). Note that the four covalent bonds are still present. There is, however, an additional fifth electron due to the impurity atom, which is *unassociated* with any particular covalent bond. This remaining electron, loosely bound to its parent (antimony) atom, is relatively free to move within the newly formed *n*-type material. Since the inserted impurity atom has donated a relatively "free" electron to the structure:

Diffused impurities with five valence electrons are called donor atoms.

It is important to realize that even though a large number of "free" carriers have been established in the *n*-type material, it is still electrically *neutral* since ideally the number of positively charged protons in the nuclei is still equal to the number of "free" and orbiting negatively charged electrons in the structure.

The effect of this doping process on the relative conductivity can best be described through the use of the energy-band diagram of Fig. 1.10. Note that a discrete energy level (called the *donor level*) appears in the forbidden band with an E_g significantly less than that of the intrinsic material. Those "free" electrons due to the added impurity sit at this energy level and have less difficulty absorbing a sufficient measure of thermal energy to move into the conduction band at room temperature. The result is that at room temperature, there are a large number of carriers (electrons) in the conduction level and the conductivity of the material increases significantly. At room temperature in an intrinsic Si material there is about one free electron for every 10^{12} atoms (1 to 10^9 for Ge). If our dosage level were 1 in 10 million (10^7), the ratio ($10^{12}/10^7 = 10^5$) would indicate that the carrier concentration has increased by a ratio of 100,000 : 1.

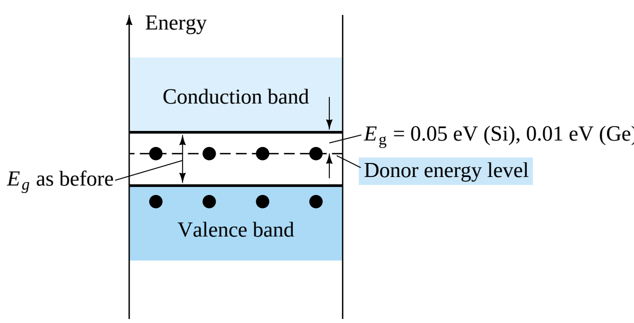


Figure 1.10 Effect of donor impurities on the energy band structure.

p-Type Material

The *p*-type material is formed by doping a pure germanium or silicon crystal with impurity atoms having *three* valence electrons. The elements most frequently used for this purpose are *boron*, *gallium*, and *indium*. The effect of one of these elements, boron, on a base of silicon is indicated in Fig. 1.11.

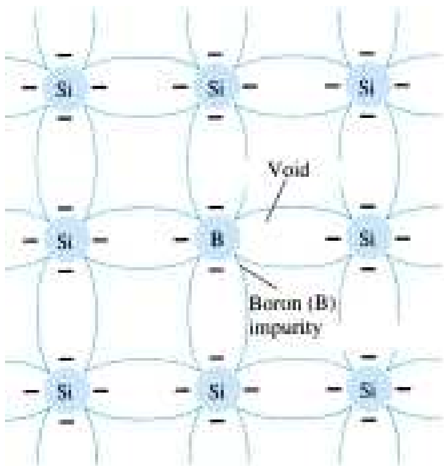


Figure 1.11 Boron impurity in *p*-type material.

Note that there is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called a *hole* and is represented by a small circle or positive sign due to the absence of a negative charge. Since the resulting vacancy will readily *accept* a "free" electron:

The diffused impurities with three valence electrons are called acceptor atoms.

The resulting *p*-type material is electrically neutral, for the same reasons described for the *n*-type material.

Electron versus Hole Flow

The effect of the hole on conduction is shown in Fig. 1.12. If a valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by a hole, then a vacancy, or hole, will be created in the covalent bond that released the electron. There is, therefore, a transfer of holes to the left and electrons to the right, as shown in Fig. 1.12. The direction to be used in this text is that of *conventional flow,* which is indicated by the direction of hole flow.

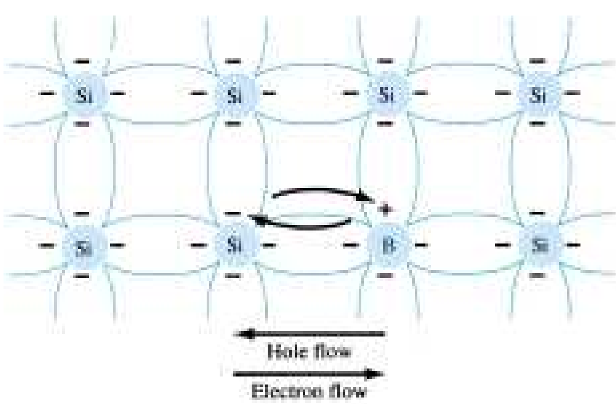


Figure 1.12 Electron versus hole flow.

Majority and Minority Carriers

In the intrinsic state, the number of free electrons in Ge or Si is due only to those few electrons in the valence band that have acquired sufficient energy from thermal or light sources to break the covalent bond or to the few impurities that could not be removed. The vacancies left behind in the covalent bonding structure represent our very limited supply of holes. In an *n*-type material, the number of holes has not changed significantly from this intrinsic level. The net result, therefore, is that the number of electrons far outweighs the number of holes. For this reason:

In an n-type material (Fig. 1.13a) the electron is called the majority carrier and the hole the minority carrier.

For the *p*-type material the number of holes far outweighs the number of electrons, as shown in Fig. 1.13b. Therefore:

In a p-type material the hole is the majority carrier and the electron is the minority carrier.

When the fifth electron of a donor atom leaves the parent atom, the atom remaining acquires a net positive charge: hence the positive sign in the donor-ion representation. For similar reasons, the negative sign appears in the acceptor ion.

The *n*- and *p*-type materials represent the basic building blocks of semiconductor devices. We will find in the next section that the “joining” of a single *n*-type material with a *p*-type material will result in a semiconductor element of considerable importance in electronic systems.

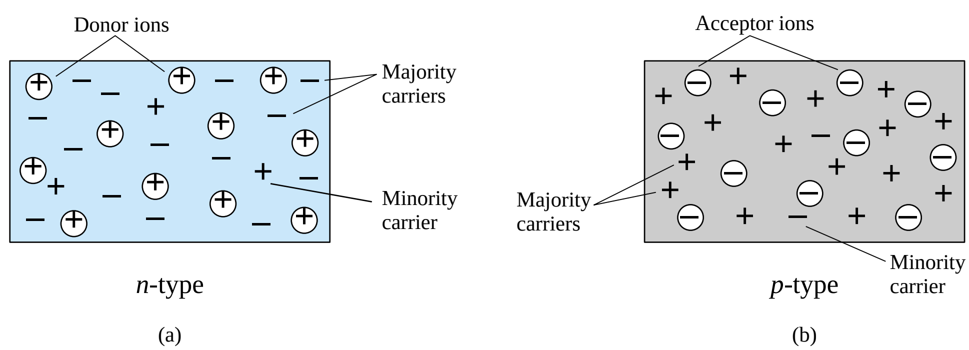


Figure 1.13 (a) *n*-type material; (b) *p*-type material.

1.6 SEMICONDUCTOR DIODE

In Section 1.5 both the *n*- and *p*-type materials were introduced. The semiconductor diode is formed by simply bringing these materials together (constructed from the same base—Ge or Si), as shown in Fig. 1.14, using techniques to be described in Chapter 20. At the instant the two materials are “joined” the electrons and holes in the region of the junction will combine, resulting in a lack of carriers in the region near the junction.

This region of uncovered positive and negative ions is called the depletion region due to the depletion of carriers in this region.

Since the diode is a two-terminal device, the application of a voltage across its terminals leaves three possibilities: *no bias* ($V_D = 0$ V), *forward bias* ($V_D > 0$ V), and *reverse bias* ($V_D < 0$ V). Each is a condition that will result in a response that the user must clearly understand if the device is to be applied effectively.

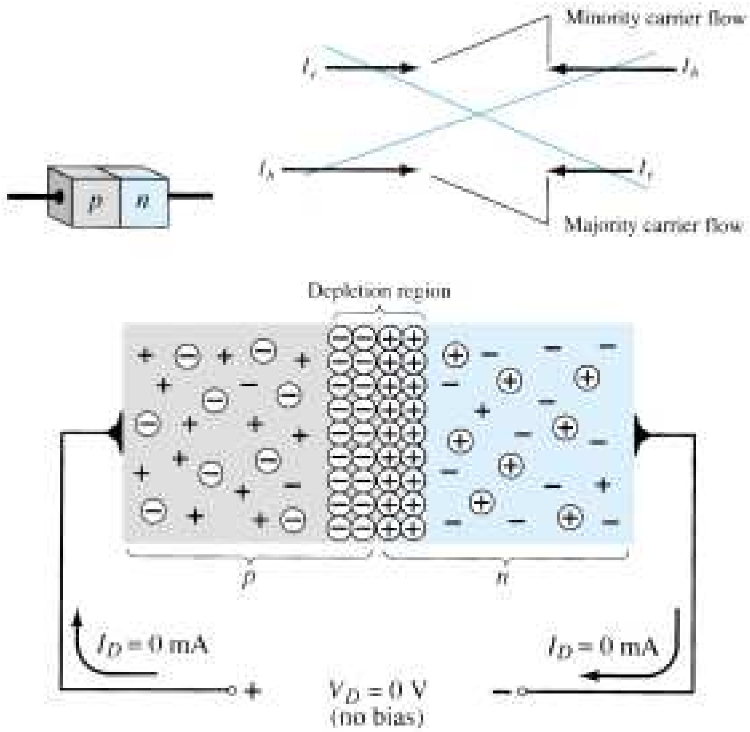


Figure 1.14 *p-n* junction with no external bias.

No Applied Bias ($V_D = 0$ V)

Under no-bias (no applied voltage) conditions, any minority carriers (holes) in the *n*-type material that find themselves within the depletion region will pass directly into the *p*-type material. The closer the minority carrier is to the junction, the greater the attraction for the layer of negative ions and the less the opposition of the positive ions in the depletion region of the *n*-type material. For the purposes of future discussions we shall assume that all the minority carriers of the *n*-type material that find themselves in the depletion region due to their random motion will pass directly into the *p*-type material. Similar discussion can be applied to the minority carriers (electrons) of the *p*-type material. This carrier flow has been indicated in Fig. 1.14 for the minority carriers of each material.

The majority carriers (electrons) of the *n*-type material must overcome the attractive forces of the layer of positive ions in the *n*-type material and the shield of negative ions in the *p*-type material to migrate into the area beyond the depletion region of the *p*-type material. However, the number of majority carriers is so large in the *n*-type material that there will invariably be a small number of majority carriers with sufficient kinetic energy to pass through the depletion region into the *p*-type material. Again, the same type of discussion can be applied to the majority carriers (holes) of the *p*-type material. The resulting flow due to the majority carriers is also shown in Fig. 1.14.

A close examination of Fig. 1.14 will reveal that the relative magnitudes of the flow vectors are such that the net flow in either direction is zero. This cancellation of vectors has been indicated by crossed lines. The length of the vector representing hole flow has been drawn longer than that for electron flow to demonstrate that the magnitude of each need not be the same for cancellation and that the doping levels for each material may result in an unequal carrier flow of holes and electrons. In summary, therefore:

In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.

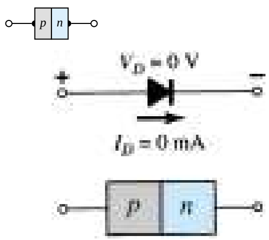


Figure 1.15 No-bias conditions for a semiconductor diode.

The symbol for a diode is repeated in Fig. 1.15 with the associated *n*- and *p*-type regions. Note that the arrow is associated with the *p*-type component and the bar with the *n*-type region. As indicated, for $V_D = 0$ V, the current in any direction is 0 mA.

Reverse-Bias Condition ($V_D < 0$ V)

If an external potential of *V* volts is applied across the *p*-*n* junction such that the positive terminal is connected to the *n*-type material and the negative terminal is connected to the *p*-type material as shown in Fig. 1.16, the number of uncovered positive ions in the depletion region of the *n*-type material will increase due to the large number of "free" electrons drawn to the positive potential of the applied voltage. For similar reasons, the number of uncovered negative ions will increase in the *p*-type material. The net effect, therefore, is a widening of the depletion region. This widening of the depletion region will establish too great a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero as shown in Fig. 1.16.

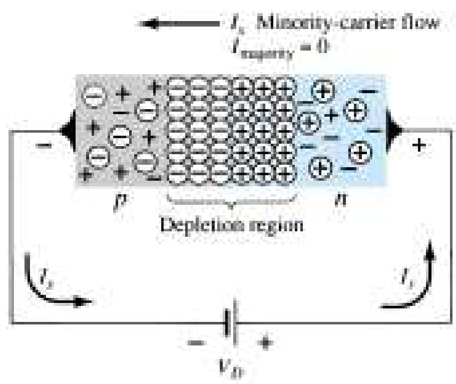


Figure 1.16 Reverse-biased *p*-*n* junction.

The number of minority carriers, however, that find themselves entering the depletion region will not change, resulting in minority-carrier flow vectors of the same magnitude indicated in Fig. 1.14 with no applied voltage.

The current that exists under reverse-bias conditions is called the reverse saturation current and is represented by I_s.

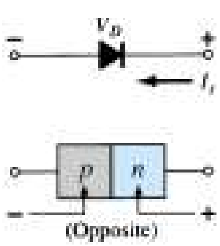


Figure 1.17 Reverse-bias conditions for a semiconductor diode.

The reverse saturation current is seldom more than a few microamperes except for high-power devices. In fact, in recent years its level is typically in the nanoampere range for silicon devices and in the low-microampere range for germanium. The term *saturation* comes from the fact that it reaches its maximum level quickly and does not change significantly with increase in the reverse-bias potential, as shown on the diode characteristics of Fig. 1.19 for $V_D < 0$ V. The reverse-biased conditions are depicted in Fig. 1.17 for the diode symbol and *p*-*n* junction. Note, in particular, that the direction of I_s is against the arrow of the symbol. Note also that the negative potential is connected to the *p*-type material and the positive potential to the *n*-type material—the difference in underlined letters for each region revealing a reverse-bias condition.

Forward-Bias Condition ($V_D > 0$ V)

A *forward-bias* or "on" condition is established by applying the positive potential to the *p*-type material and the negative potential to the *n*-type material as shown in Fig. 1.18. For future reference, therefore:

A semiconductor diode is forward-biased when the association p*-type and positive and* n*-type and negative has been established.*

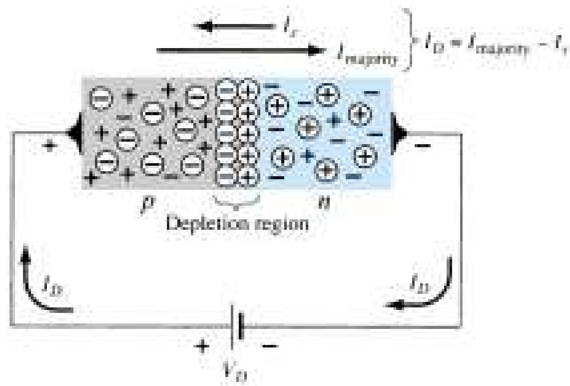


Figure 1.18 Forward-biased *p-n* junction.

The application of a forward-bias potential V_D will "pressure" electrons in the *n*-type material and holes in the *p*-type material to recombine with the ions near the boundary and reduce the width of the depletion region as shown in Fig. 1.18. The resulting minority-carrier flow of electrons from the *p*-type material to the *n*-type material (and of holes from the *n*-type material to the *p*-type material) has not changed in magnitude (since the conduction level is controlled primarily by the limited number of impurities in the material), but the reduction in the width of the depletion region has resulted in a heavy majority flow across the junction. An electron of the *n*-type material now "sees" a reduced barrier at the junction due to the reduced depletion region and a strong attraction for the positive potential applied to the *p*-type material. As the applied bias increases in magnitude the depletion region will continue to decrease in width until a flood of electrons can pass through the junction, re-

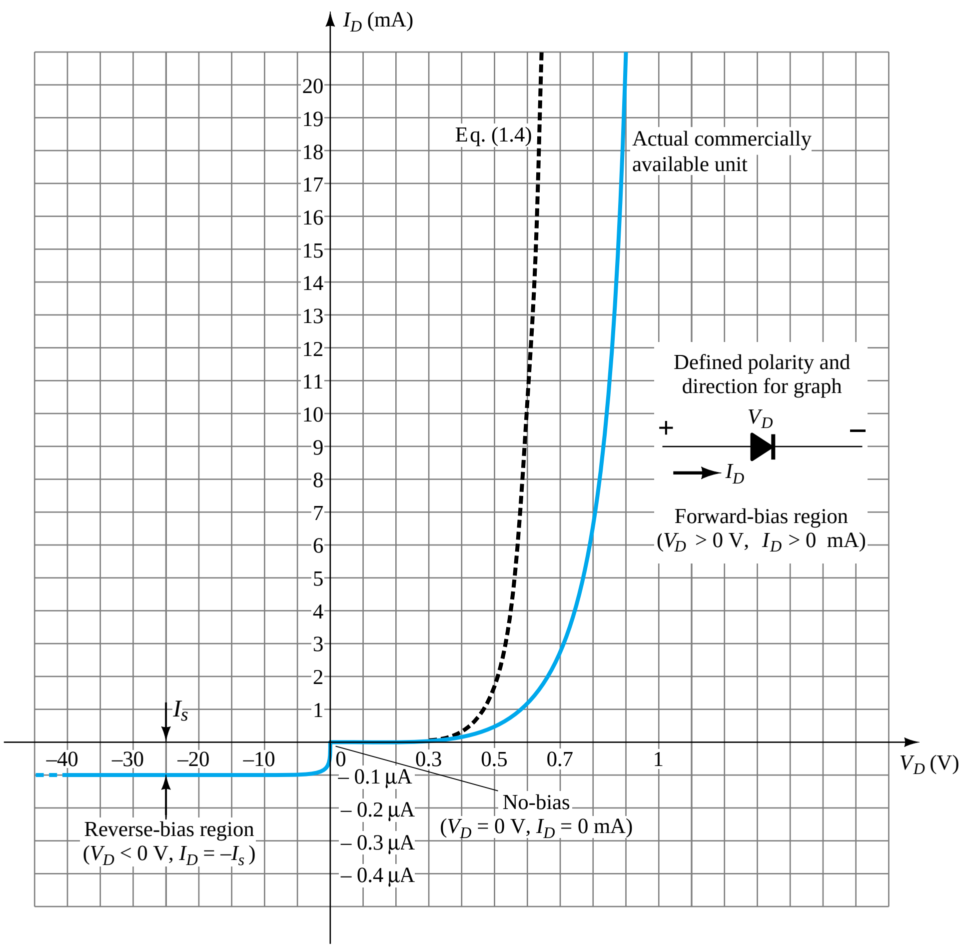


Figure 1.19 Silicon semiconductor diode characteristics.

sulting in an exponential rise in current as shown in the forward-bias region of the characteristics of Fig. 1.19. Note that the vertical scale of Fig. 1.19 is measured in milliamperes (although some semiconductor diodes will have a vertical scale measured in amperes) and the horizontal scale in the forward-bias region has a maximum of 1 V. Typically, therefore, the voltage across a forward-biased diode will be less than 1 V. Note also, how quickly the current rises beyond the knee of the curve.

It can be demonstrated through the use of solid-state physics that the general characteristics of a semiconductor diode can be defined by the following equation for the forward- and reverse-bias regions:

$$\boxed{I_D = I_s(e^{kV_D/T_K} - 1)} \qquad (1.4)$$

where I_s = reverse saturation current

$k = 11{,}600/\eta$ with $\eta = 1$ for Ge and $\eta = 2$ for Si for relatively low levels of diode current (at or below the knee of the curve) and $\eta = 1$ for Ge and Si for higher levels of diode current (in the rapidly increasing section of the curve)

$T_K = T_C + 273°$

A plot of Eq. (1.4) is provided in Fig. 1.19. If we expand Eq. (1.4) into the following form, the contributing component for each region of Fig. 1.19 can easily be described:

$$I_D = I_s e^{kV_D/T_K} - I_s$$

For positive values of V_D the first term of the equation above will grow very quickly and overpower the effect of the second term. The result is that for positive values of V_D, I_D will be positive and grow as the function $y = e^x$ appearing in Fig. 1.20. At $V_D = 0$ V, Eq. (1.4) becomes $I_D = I_s(e^0 - 1) = I_s(1 - 1) = 0$ mA as appearing in Fig. 1.19. For negative values of V_D the first term will quickly drop off below I_s, resulting in $I_D = -I_s$, which is simply the horizontal line of Fig. 1.19. The break in the characteristics at $V_D = 0$ V is simply due to the dramatic change in scale from mA to μA.

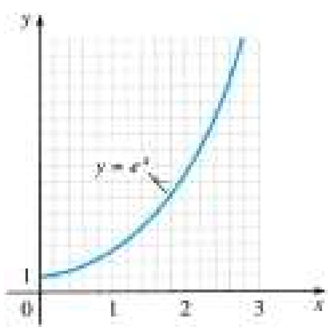


Figure 1.20 Plot of e^x.

Note in Fig. 1.19 that the commercially available unit has characteristics that are shifted to the right by a few tenths of a volt. This is due to the internal "body" resistance and external "contact" resistance of a diode. Each contributes to an additional voltage at the same current level as determined by Ohm's law ($V = IR$). In time, as production methods improve, this difference will decrease and the actual characteristics approach those of Eq. (1.4).

It is important to note the change in scale for the vertical and horizontal axes. For positive values of I_D the scale is in milliamperes and the current scale below the axis is in microamperes (or possibly nanoamperes). For V_D the scale for positive values is in tenths of volts and for negative values the scale is in tens of volts.

Initially, Eq. (1.4) does appear somewhat complex and may develop an unwarranted fear that it will be applied for all the diode applications to follow. Fortunately, however, a number of approximations will be made in a later section that will negate the need to apply Eq. (1.4) and provide a solution with a minimum of mathematical difficulty.

Before leaving the subject of the forward-bias state the conditions for conduction (the "on" state) are repeated in Fig. 1.21 with the required biasing polarities and the resulting direction of majority-carrier flow. Note in particular how the direction of conduction matches the arrow in the symbol (as revealed for the ideal diode).

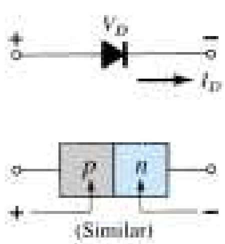


Figure 1.21 Forward-bias conditions for a semiconductor diode.

Zener Region

Even though the scale of Fig. 1.19 is in tens of volts in the negative region, there is a point where the application of too negative a voltage will result in a sharp change

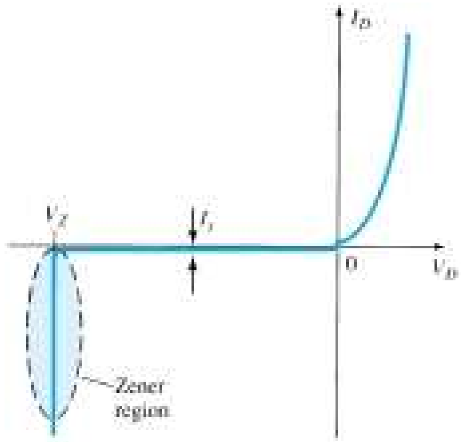


Figure 1.22 Zener region.

in the characteristics, as shown in Fig. 1.22. The current increases at a very rapid rate in a direction opposite to that of the positive voltage region. The reverse-bias potential that results in this dramatic change in characteristics is called the *Zener potential* and is given the symbol V_Z.

As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase. Eventually, their velocity and associated kinetic energy ($W_K = \frac{1}{2}mv^2$) will be sufficient to release additional carriers through collisions with otherwise stable atomic structures. That is, an *ionization* process will result whereby valence electrons absorb sufficient energy to leave the parent atom. These additional carriers can then aid the ionization process to the point where a high *avalanche* current is established and the *avalanche breakdown* region determined.

The avalanche region (V_Z) can be brought closer to the vertical axis by increasing the doping levels in the *p*- and *n*-type materials. However, as V_Z decreases to very low levels, such as −5 V, another mechanism, called *Zener breakdown,* will contribute to the sharp change in the characteristic. It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and "generate" carriers. Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_Z, this sharp change in the characteristic at any level is called the *Zener region* and diodes employing this unique portion of the characteristic of a *p-n* junction are called *Zener diodes.* They are described in detail in Section 1.14.

The Zener region of the semiconductor diode described must be avoided if the response of a system is not to be completely altered by the sharp change in characteristics in this reverse-voltage region.

The maximum reverse-bias potential that can be applied before entering the Zener region is called the peak inverse voltage (referred to simply as the PIV rating) or the peak reverse voltage (denoted by PRV rating).

If an application requires a PIV rating greater than that of a single unit, a number of diodes of the same characteristics can be connected in series. Diodes are also connected in parallel to increase the current-carrying capacity.

Silicon versus Germanium

Silicon diodes have, in general, higher PIV and current rating and wider temperature ranges than germanium diodes. PIV ratings for silicon can be in the neighborhood of 1000 V, whereas the maximum value for germanium is closer to 400 V. Silicon can be used for applications in which the temperature may rise to about 200°C (400°F), whereas germanium has a much lower maximum rating (100°C). The disadvantage of silicon, however, as compared to germanium, as indicated in Fig. 1.23, is the higher

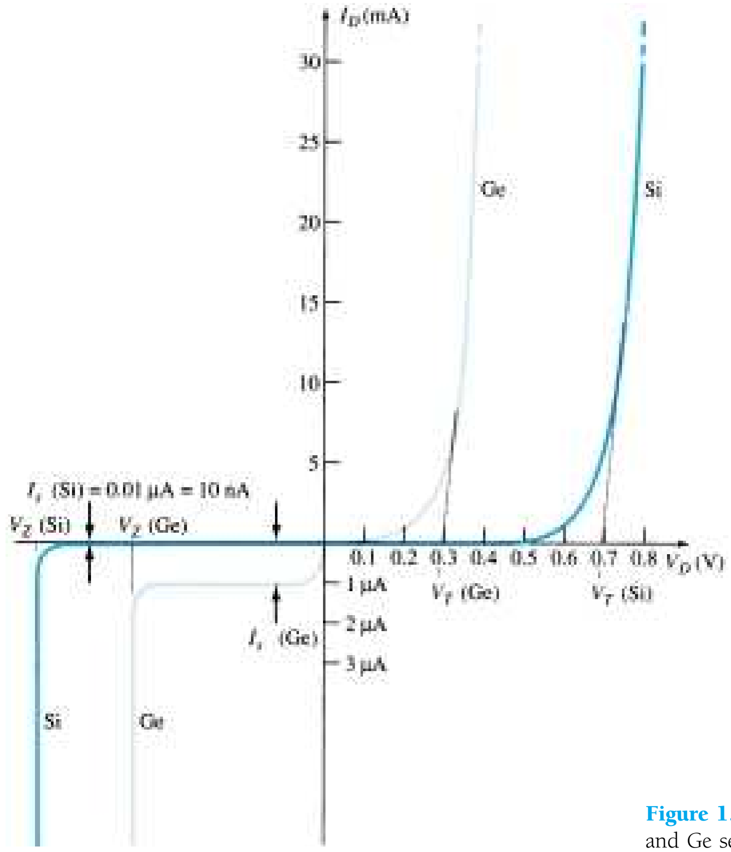


Figure 1.23 Comparison of Si and Ge semiconductor diodes.

forward-bias voltage required to reach the region of upward swing. It is typically of the order of magnitude of 0.7 V for *commercially* available silicon diodes and 0.3 V for germanium diodes when rounded off to the nearest tenths. The increased offset for silicon is due primarily to the factor η in Eq. (1.4). This factor plays a part in determining the shape of the curve only at very low current levels. Once the curve starts its vertical rise, the factor η drops to 1 (the continuous value for germanium). This is evidenced by the similarities in the curves once the offset potential is reached. The potential at which this rise occurs is commonly referred to as the *offset, threshold,* or *firing potential.* Frequently, the first letter of a term that describes a particular quantity is used in the notation for that quantity. However, to ensure a minimum of confusion with other terms, such as output voltage (V_o) and forward voltage (V_F), the notation V_T has been adopted for this book, from the word "threshold."

In review:

$$V_T = 0.7 \text{ (Si)}$$
$$V_T = 0.3 \text{ (Ge)}$$

Obviously, the closer the upward swing is to the vertical axis, the more "ideal" the device. However, the other characteristics of silicon as compared to germanium still make it the choice in the majority of commercially available units.

Temperature Effects

Temperature can have a marked effect on the characteristics of a silicon semiconductor diode as witnessed by a typical silicon diode in Fig. 1.24. It has been found experimentally that:

The reverse saturation current I_s will just about double in magnitude for every 10°C increase in temperature.

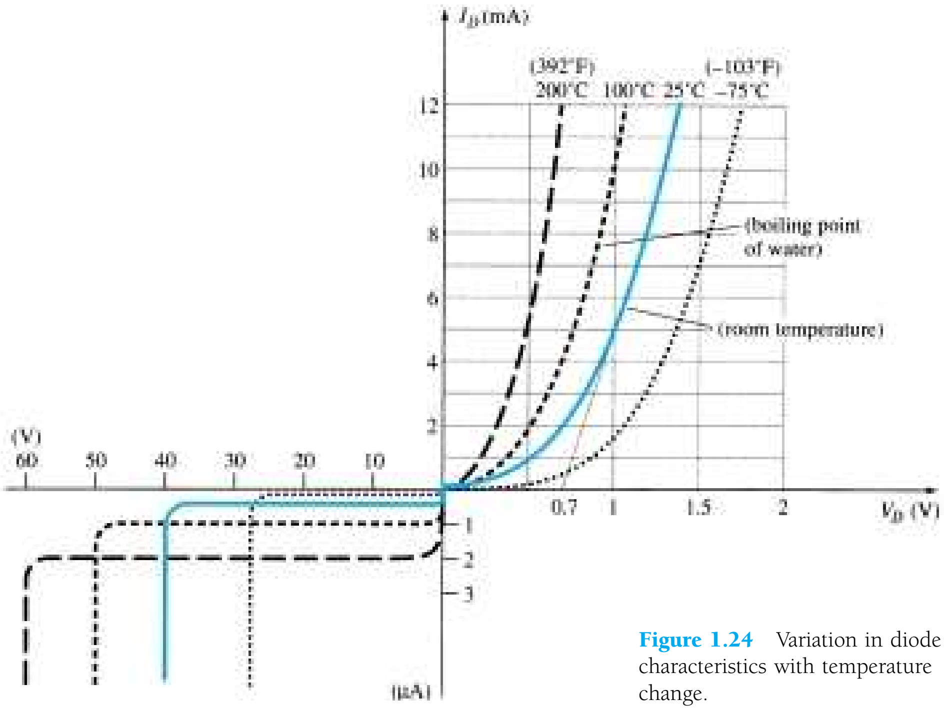


Figure 1.24 Variation in diode characteristics with temperature change.

It is not uncommon for a germanium diode with an I_s in the order of 1 or 2 μA at 25°C to have a leakage current of 100 $\mu\text{A} = 0.1$ mA at a temperature of 100°C. Current levels of this magnitude in the reverse-bias region would certainly question our desired open-circuit condition in the reverse-bias region. Typical values of I_s for silicon are much lower than that of germanium for similar power and current levels as shown in Fig. 1.23. The result is that even at high temperatures the levels of I_s for silicon diodes do not reach the same high levels obtained for germanium—a very important reason that silicon devices enjoy a significantly higher level of development and utilization in design. Fundamentally, the open-circuit equivalent in the reverse-bias region is better realized at any temperature with silicon than with germanium.

The increasing levels of I_s with temperature account for the lower levels of threshold voltage, as shown in Fig. 1.24. Simply increase the level of I_s in Eq. (1.4) and note the earlier rise in diode current. Of course, the level of T_K also will be increasing in the same equation, but the increasing level of I_s will overpower the smaller percent change in T_K. As the temperature increases the forward characteristics are actually becoming more "ideal," but we will find when we review the specifications sheets that temperatures beyond the normal operating range can have a very detrimental effect on the diode's maximum power and current levels. In the reverse-bias region the breakdown voltage is increasing with temperature, but note the undesirable increase in reverse saturation current.

1.7 RESISTANCE LEVELS

As the operating point of a diode moves from one region to another the resistance of the diode will also change due to the nonlinear shape of the characteristic curve. It will be demonstrated in the next few paragraphs that the type of applied voltage or signal will define the resistance level of interest. Three different levels will be introduced in this section that will appear again as we examine other devices. It is therefore paramount that their determination be clearly understood.

DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D as shown in Fig. 1.25 and applying the following equation:

$$R_D = \frac{V_D}{I_D} \qquad (1.5)$$

The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high. Since ohmmeters typically employ a relatively constant-current source, the resistance determined will be at a preset current level (typically, a few milliamperes).

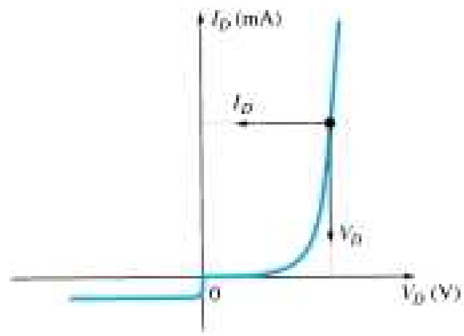


Figure 1.25 Determining the dc resistance of a diode at a particular operating point.

In general, therefore, the lower the current through a diode the higher the dc resistance level.

EXAMPLE 1.1

Determine the dc resistance levels for the diode of Fig. 1.26 at

(a) $I_D = 2$ mA
(b) $I_D = 20$ mA
(c) $V_D = -10$ V

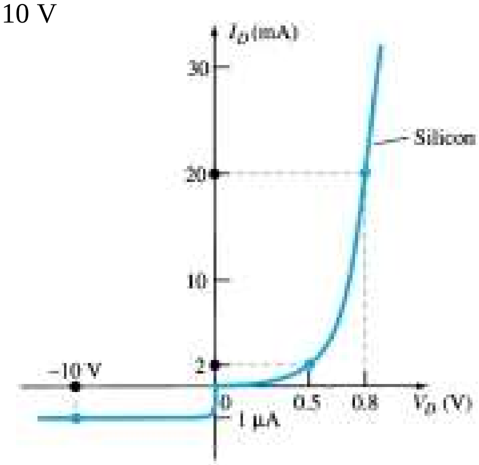


Figure 1.26 Example 1.1

Solution

(a) At $I_D = 2$ mA, $V_D = 0.5$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.5\text{ V}}{2\text{ mA}} = \mathbf{250\ \Omega}$$

(b) At $I_D = 20$ mA, $V_D = 0.8$ V (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{0.8 \text{ V}}{20 \text{ mA}} = \mathbf{40\ \Omega}$$

(c) At $V_D = -10$ V, $I_D = -I_s = -1\ \mu$A (from the curve) and

$$R_D = \frac{V_D}{I_D} = \frac{10 \text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

clearly supporting some of the earlier comments regarding the dc resistance levels of a diode.

AC or Dynamic Resistance

It is obvious from Eq. 1.5 and Example 1.1 that the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest. If a sinusoidal rather than dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Fig. 1.27. With no applied varying signal, the point of operation would be the *Q*-point appearing on Fig. 1.27 determined by the applied dc levels. The designation *Q-point* is derived from the word *quiescent*, which means "still or unvarying."

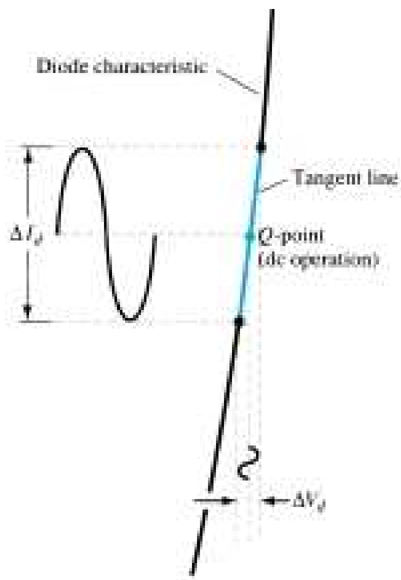


Figure 1.27 Defining the dynamic or ac resistance.

A straight line drawn tangent to the curve through the *Q*-point as shown in Fig. 1.28 will define a particular change in voltage and current that can be used to determine the *ac* or *dynamic* resistance for this region of the diode characteristics. An effort should be made to keep the change in voltage and current as small as possible and equidistant to either side of the *Q*-point. In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d} \quad \text{where } \Delta \text{ signifies a finite change in the quantity.} \quad (1.6)$$

The steeper the slope, the less the value of ΔV_d for the same change in ΔI_d and the less the resistance. The ac resistance in the vertical-rise region of the characteristic is therefore quite small, while the ac resistance is much higher at low current levels.

In general, therefore, the lower the Q-point of operation (smaller current or lower voltage) the higher the ac resistance.

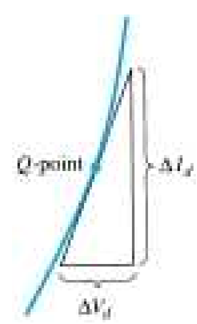


Figure 1.28 Determining the ac resistance at a *Q*-point.

EXAMPLE 1.2

For the characteristics of Fig. 1.29:
(a) Determine the ac resistance at $I_D = 2$ mA.
(b) Determine the ac resistance at $I_D = 25$ mA.
(c) Compare the results of parts (a) and (b) to the dc resistances at each current level.

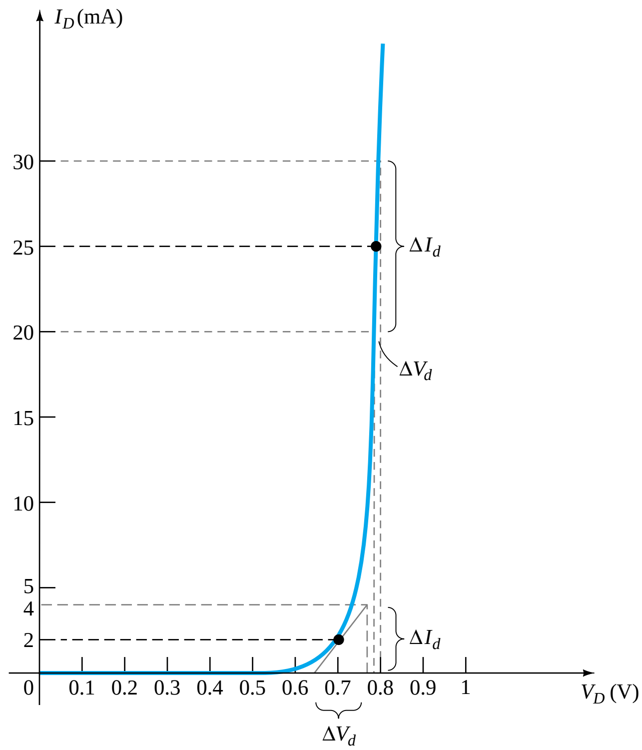


Figure 1.29 Example 1.2

Solution

(a) For $I_D = 2$ mA; the tangent line at $I_D = 2$ mA was drawn as shown in the figure and a swing of 2 mA above and below the specified diode current was chosen. At $I_D = 4$ mA, $V_D = 0.76$ V, and at $I_D = 0$ mA, $V_D = 0.65$ V. The resulting changes in current and voltage are

$$\Delta I_d = 4\text{ mA} - 0\text{ mA} = 4\text{ mA}$$

and

$$\Delta V_d = 0.76\text{ V} - 0.65\text{ V} = 0.11\text{ V}$$

and the ac resistance:

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.11\text{ V}}{4\text{ mA}} = \mathbf{27.5\ \Omega}$$

(b) For $I_D = 25$ mA, the tangent line at $I_D = 25$ mA was drawn as shown on the figure and a swing of 5 mA above and below the specified diode current was chosen. At $I_D = 30$ mA, $V_D = 0.8$ V, and at $I_D = 20$ mA, $V_D = 0.78$ V. The resulting changes in current and voltage are

$$\Delta I_d = 30\text{ mA} - 20\text{ mA} = 10\text{ mA}$$

and

$$\Delta V_d = 0.8\text{ V} - 0.78\text{ V} = 0.02\text{ V}$$

and the ac resistance is

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{0.02\text{ V}}{10\text{ mA}} = \mathbf{2\ \Omega}$$

(c) For $I_D = 2$ mA, $V_D = 0.7$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.7\text{ V}}{2\text{ mA}} = \mathbf{350\ \Omega}$$

which far exceeds the r_d of 27.5 Ω.

For $I_D = 25$ mA, $V_D = 0.79$ V and

$$R_D = \frac{V_D}{I_D} = \frac{0.79\text{ V}}{25\text{ mA}} = \mathbf{31.62\ \Omega}$$

which far exceeds the r_d of 2 Ω.

We have found the dynamic resistance graphically, but there is a basic definition in differential calculus which states:

The derivative of a function at a point is equal to the slope of the tangent line drawn at that point.

Equation (1.6), as defined by Fig. 1.28, is, therefore, essentially finding the derivative of the function at the Q-point of operation. If we find the derivative of the general equation (1.4) for the semiconductor diode with respect to the applied forward bias and then invert the result, we will have an equation for the dynamic or ac resistance in that region. That is, taking the derivative of Eq. (1.4) with respect to the applied bias will result in

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV}[I_s(e^{kV_D/T_K} - 1)]$$

and

$$\frac{dI_D}{dV_D} = \frac{k}{T_K}(I_D + I_s)$$

following a few basic maneuvers of differential calculus. In general, $I_D \gg I_s$ in the vertical slope section of the characteristics and

$$\frac{dI_D}{dV_D} \cong \frac{k}{T_K} I_D$$

Substituting $\eta = 1$ for Ge and Si in the vertical-rise section of the characteristics, we obtain

$$k = \frac{11{,}600}{\eta} = \frac{11{,}600}{1} = 11{,}600$$

and at room temperature,

$$T_K = T_C + 273° = 25° + 273° = 298°$$

so that

$$\frac{k}{T_K} = \frac{11{,}600}{298} \cong 38.93$$

and

$$\frac{dI_D}{dV_D} = 38.93 I_D$$

Flipping the result to define a resistance ratio ($R = V/I$) gives us

$$\frac{dV_D}{dI_D} \cong \frac{0.026}{I_D}$$

or

$$\boxed{r_d = \frac{26\text{ mV}}{I_D}}_{\text{Ge,Si}} \qquad (1.7)$$

The significance of Eq. (1.7) must be clearly understood. It implies that the dynamic resistance can be found simply by substituting the quiescent value of the diode current into the equation. There is no need to have the characteristics available or to worry about sketching tangent lines as defined by Eq. (1.6). It is important to keep in mind, however, that Eq. (1.7) is accurate only for values of I_D in the vertical-rise section of the curve. For lesser values of I_D, $\eta = 2$ (silicon) and the value of r_d obtained must be multiplied by a factor of 2. For small values of I_D below the knee of the curve, Eq. (1.7) becomes inappropriate.

All the resistance levels determined thus far have been defined by the *p-n* junction and do not include the resistance of the semiconductor material itself (called *body* resistance) and the resistance introduced by the connection between the semiconductor material and the external metallic conductor (called *contact* resistance). These additional resistance levels can be included in Eq. (1.7) by adding resistance denoted by r_B as appearing in Eq. (1.8). The resistance r'_d, therefore, includes the dynamic resistance defined by Eq. 1.7 and the resistance r_B just introduced.

$$r'_d = \frac{26 \text{ mV}}{I_D} + r_B \qquad \text{ohms} \tag{1.8}$$

The factor r_B can range from typically 0.1 Ω for high-power devices to 2 Ω for some low-power, general-purpose diodes. For Example 1.2 the ac resistance at 25 mA was calculated to be 2 Ω. Using Eq. (1.7), we have

$$r_d = \frac{26 \text{ mV}}{I_D} = \frac{26 \text{ mV}}{25 \text{ mA}} = \mathbf{1.04\ \Omega}$$

The difference of about 1 Ω could be treated as the contribution of r_B.

For Example 1.2 the ac resistance at 2 mA was calculated to be 27.5 Ω. Using Eq. (1.7) but multiplying by a factor of 2 for this region (in the knee of the curve $\eta = 2$),

$$r_d = 2\left(\frac{26 \text{ mV}}{I_D}\right) = 2\left(\frac{26 \text{ mV}}{2 \text{ mA}}\right) = 2(13\ \Omega) = \mathbf{26\ \Omega}$$

The difference of 1.5 Ω could be treated as the contribution due to r_B.

In reality, determining r_d to a high degree of accuracy from a characteristic curve using Eq. (1.6) is a difficult process at best and the results have to be treated with a grain of salt. At low levels of diode current the factor r_B is normally small enough compared to r_d to permit ignoring its impact on the ac diode resistance. At high levels of current the level of r_B may approach that of r_d, but since there will frequently be other resistive elements of a much larger magnitude in series with the diode we will assume in this book that the ac resistance is determined solely by r_d and the impact of r_B will be ignored unless otherwise noted. Technological improvements of recent years suggest that the level of r_B will continue to decrease in magnitude and eventually become a factor that can certainly be ignored in comparison to r_d.

The discussion above has centered solely on the forward-bias region. In the reverse-bias region we will assume that the change in current along the I_s line is nil from 0 V to the Zener region and the resulting ac resistance using Eq. (1.6) is sufficiently high to permit the open-circuit approximation.

Average AC Resistance

If the input signal is sufficiently large to produce a broad swing such as indicated in Fig. 1.30, the resistance associated with the device for this region is called the *average ac resistance.* The average ac resistance is, by definition, the resistance deter-

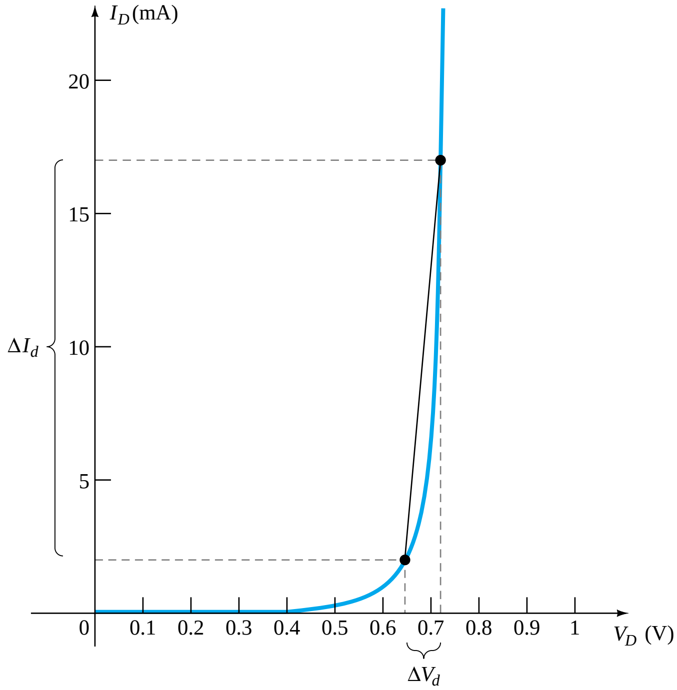


Figure 1.30 Determining the average ac resistance between indicated limits.

mined by a straight line drawn between the two intersections established by the maximum and minimum values of input voltage. In equation form (note Fig. 1.30),

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} \tag{1.9}$$

For the situation indicated by Fig. 1.30,

$$\Delta I_d = 17 \text{ mA} - 2 \text{ mA} = 15 \text{ mA}$$

and $$\Delta V_d = 0.725 \text{ V} - 0.65 \text{ V} = 0.075 \text{ V}$$

with $$r_{av} = \frac{\Delta V_d}{\Delta I_d} = \frac{0.075 \text{ V}}{15 \text{ mA}} = \mathbf{5\ \Omega}$$

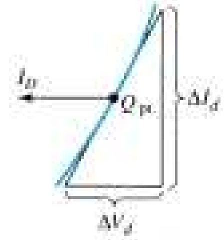
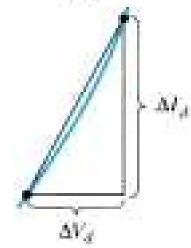
If the ac resistance (r_d) were determined at $I_D = 2$ mA its value would be more than 5 Ω, and if determined at 17 mA it would be less. In between the ac resistance would make the transition from the high value at 2 mA to the lower value at 17 mA. Equation (1.9) has defined a value that is considered the average of the ac values from 2 to 17 mA. The fact that one resistance level can be used for such a wide range of the characteristics will prove quite useful in the definition of equivalent circuits for a diode in a later section.

As with the dc and ac resistance levels, the lower the level of currents used to determine the average resistance the higher the resistance level.

Summary Table

Table 1.2 was developed to reinforce the important conclusions of the last few pages and to emphasize the differences among the various resistance levels. As indicated earlier, the content of this section is the foundation for a number of resistance calculations to be performed in later sections and chapters.

TABLE 1.2 Resistance Levels

Type	*Equation*	*Special Characteristics*	*Graphical Determination*
DC or static	$R_D = \dfrac{V_D}{I_D}$	Defined as a *point* on the characteristics	
AC or dynamic	$r_d = \dfrac{\Delta V_d}{\Delta I_d} = \dfrac{26\text{ mV}}{I_D}$	Defined by a tangent line at the Q-point	
Average ac	$r_{av} = \dfrac{\Delta V_d}{\Delta I_d}\Big\vert_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

1.8 DIODE EQUIVALENT CIRCUITS

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region.

In other words, once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit inserted in its place without severely affecting the actual behavior of the system. The result is often a network that can be solved using traditional circuit analysis techniques.

Piecewise-Linear Equivalent Circuit

One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments, as shown in Fig. 1.31. The resulting equivalent circuit is naturally called the *piecewise-linear equivalent circuit.* It should be obvious from Fig. 1.31 that the straight-line segments do not result in an exact duplication of the actual characteristics, especially in the knee region. However, the resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behavior of the device. For the sloping section of the equivalence the average ac resistance as introduced in Section 1.7 is the resistance level appearing in the equivalent circuit of Fig. 1.32 next to the actual device. In essence, it defines the resistance level of the device when it is in the "on" state. The ideal diode is included to establish that there is only one direction of conduction through the device, and a reverse-bias condition will re-

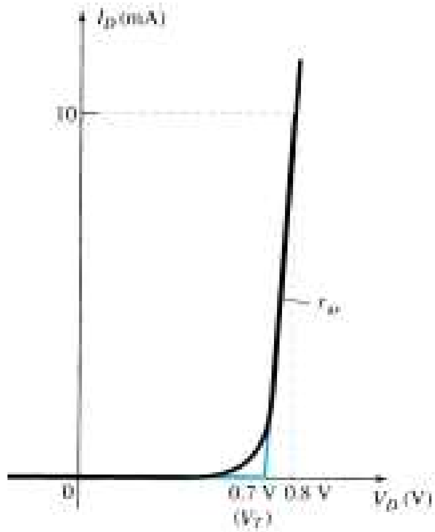


Figure 1.31 Defining the piecewise-linear equivalent circuit using straight-line segments to approximate the characteristic curve.

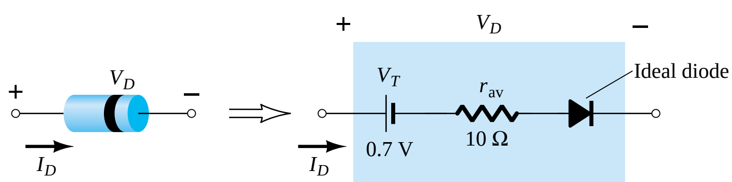


Figure 1.32 Components of the piecewise-linear equivalent circuit.

sult in the open-circuit state for the device. Since a silicon semiconductor diode does not reach the conduction state until V_D reaches 0.7 V with a forward bias (as shown in Fig. 1.31), a battery V_T opposing the conduction direction must appear in the equivalent circuit as shown in Fig. 1.32. The battery simply specifies that the voltage across the device must be greater than the threshold battery voltage before conduction through the device in the direction dictated by the ideal diode can be established. When conduction is established the resistance of the diode will be the specified value of r_{av}.

Keep in mind, however, that V_T in the equivalent circuit is not an independent voltage source. If a voltmeter is placed across an isolated diode on the top of a lab bench, a reading of 0.7 V will not be obtained. The battery simply represents the horizontal offset of the characteristics that must be exceeded to establish conduction.

The approximate level of r_{av} can usually be determined from a specified operating point on the specification sheet (to be discussed in Section 1.9). For instance, for a silicon semiconductor diode, if $I_F = 10$ mA (a forward conduction current for the diode) at $V_D = 0.8$ V, we know for silicon that a shift of 0.7 V is required before the characteristics rise and

$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} = \frac{0.8\text{ V} - 0.7\text{ V}}{10\text{ mA} - 0\text{ mA}} = \frac{0.1\text{ V}}{10\text{ mA}} = \mathbf{10\ \Omega}$$

as obtained for Fig. 1.30.

Simplified Equivalent Circuit

For most applications, the resistance r_{av} is sufficiently small to be ignored in comparison to the other elements of the network. The removal of r_{av} from the equivalent

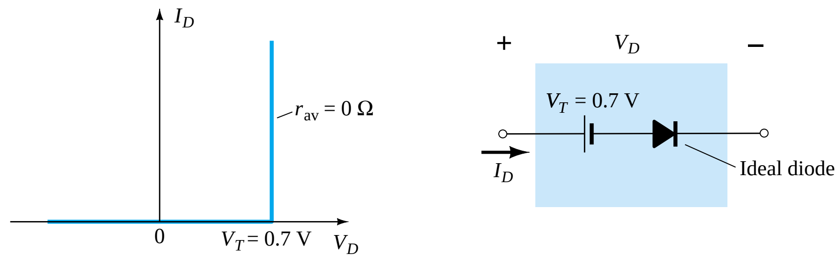


Figure 1.33 Simplified equivalent circuit for the silicon semiconductor diode.

circuit is the same as implying that the characteristics of the diode appear as shown in Fig. 1.33. Indeed, this approximation is frequently employed in semiconductor circuit analysis as demonstrated in Chapter 2. The reduced equivalent circuit appears in the same figure. It states that a forward-biased silicon diode in an electronic system under dc conditions has a drop of 0.7 V across it in the conduction state at any level of diode current (within rated values, of course).

Ideal Equivalent Circuit

Now that r_{av} has been removed from the equivalent circuit let us take it a step further and establish that a 0.7-V level can often be ignored in comparison to the applied voltage level. In this case the equivalent circuit will be reduced to that of an ideal diode as shown in Fig. 1.34 with its characteristics. In Chapter 2 we will see that this approximation is often made without a serious loss in accuracy.

In industry a popular substitution for the phrase “diode equivalent circuit” is diode *model*—a model by definition being a representation of an existing device, object, system, and so on. In fact, this substitute terminology will be used almost exclusively in the chapters to follow.

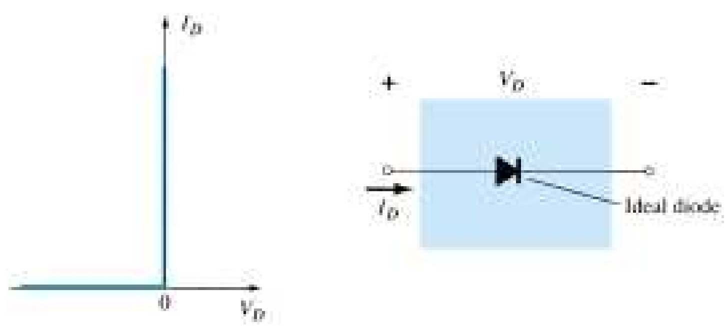
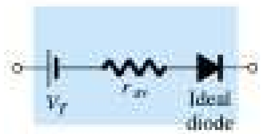
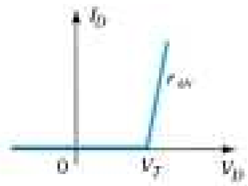
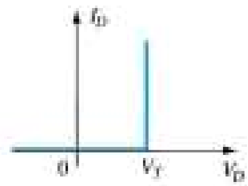
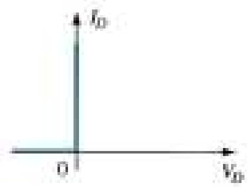


Figure 1.34 Ideal diode and its characteristics.

Summary Table

For clarity, the diode models employed for the range of circuit parameters and applications are provided in Table 1.3 with their piecewise-linear characteristics. Each will be investigated in greater detail in Chapter 2. There are always exceptions to the general rule, but it is fairly safe to say that the simplified equivalent model will be employed most frequently in the analysis of electronic systems while the ideal diode is frequently applied in the analysis of power supply systems where larger voltages are encountered.

TABLE 1.3 Diode Equivalent Circuits (Models)

Type	*Conditions*	*Model*	*Characteristics*
Piecewise-linear model			
Simplified model	$R_{\text{network}} \gg r_{av}$		
Ideal device	$R_{\text{network}} \gg r_{av}$ $E_{\text{network}} \gg V_T$		

1.9 DIODE SPECIFICATION SHEETS

Data on specific semiconductor devices are normally provided by the manufacturer in one of two forms. Most frequently, it is a very brief description limited to perhaps one page. Otherwise, it is a thorough examination of the characteristics using graphs, artwork, tables, and so on. In either case, there are specific pieces of data that must be included for proper utilization of the device. They include:

1. The forward voltage V_F (at a specified current and temperature)
2. The maximum forward current I_F (at a specified temperature)
3. The reverse saturation current I_R (at a specified voltage and temperature)
4. The reverse-voltage rating [PIV or PRV or V(BR), where BR comes from the term “breakdown” (at a specified temperature)]
5. The maximum power dissipation level at a particular temperature
6. Capacitance levels (as defined in Section 1.10)
7. Reverse recovery time t_{rr} (as defined in Section 1.11)
8. Operating temperature range

Depending on the type of diode being considered, additional data may also be provided, such as frequency range, noise level, switching time, thermal resistance levels, and peak repetitive values. For the application in mind, the significance of the data will usually be self-apparent. If the maximum power or dissipation rating is also provided, it is understood to be equal to the following product:

$$\boxed{P_{D\max} = V_D I_D} \qquad (1.10)$$

where I_D and V_D are the diode current and voltage at a particular point of operation.

If we apply the simplified model for a particular application (a common occurrence), we can substitute $V_D = V_T = 0.7$ V for a silicon diode in Eq. (1.10) and determine the resulting power dissipation for comparison against the maximum power rating. That is,

$$P_{dissipated} \cong (0.7\ \text{V})I_D \tag{1.11}$$

DIFFUSED SILICON PLANAR

A — • BV . . . 125 V (MIN) @ 100 μA

ABSOLUTE MAXIMUM RATINGS (Note 1)

Temperatures

B	Storage Temperature Range	−65°C to +200°C
B	Maximum Junction Operating Temperature	+175°C
B	Lead Temperature	+260°C

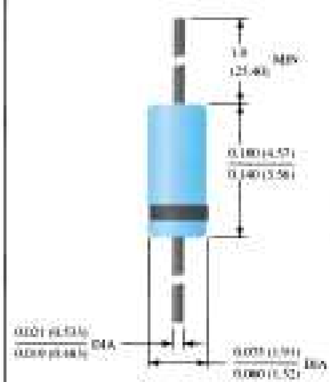
Power Dissipation (Note 2)

C	Maximum Total Power Dissipation at 25°C Ambient	500 mW
C	Linear Power Derating Factor (from 25°C)	3.33 mW/°C

Maximum Voltage and Currents

	WIV	Working Inverse Voltage	100 V
	I_O	Average Rectified Current	200 mA
D	I_F	Continuous Forward Current	500 mA
	i_f	Peak Repetitive Forward Current	600 mA
	$i_{f(surge)}$	Peak Forward Surge Current	
		Pulse Width = 1 s	1.0 A
		Pulse Width = 1 μs	4.0 A

DO-35 OUTLINE



NOTES:
Copper clad steel leads, tin plated
Gold plated leads available
Hermetically sealed glass package
Package weight is 0.14 gram

ELECTRICAL CHARACTERISTICS (25°C Ambient Temperature unless otherwise noted)

	SYMBOL	CHARACTERISTIC	MIN	MAX	UNITS	TEST CONDITIONS
E	V_F	Forward Voltage	0.85	1.00	V	I_F = 200 mA
			0.81	0.94	V	I_F = 100 mA
			0.78	0.88	V	I_F = 50 mA
			0.69	0.80	V	I_F = 10 mA
			0.67	0.75	V	I_F = 5.0 mA
F			0.60	0.68	V	I_F = 1.0 mA
					V	I_F = 0.1 mA
G	I_R	Reverse Current		500	nA	V_R = 20 V, T_A = 125°C
				5.0	nA	V_R = 100 V
				1.0	μA	V_R = 100 V, T_A = 125°C
					nA	V_R = 180 V
					μA	V_R = 180 V, T_A = 100°C
	BV	Breakdown Voltage	125		V	I_R = 100 μA
H	C	Capacitance		8.0	pF	V_R = 0, f = 1.0 MHz
I	t_{rr}	Reverse Recovery Time		3.0	μs	I_F = 10 mA, V_R = 35 V, R_L = 1.0 to 100 kΩ, C_L = 10 pF

NOTES:
1. These ratings are limiting values above which the serviceability of the diode may be impaired.
2. These are steady state limits. The factory should be consulted on applications involving pulses or low duty-cycle operation.

Figure 1.35 Electrical characteristics of a high-voltage, low-leakage diode.

An exact copy of the data provided for a high-voltage/low-leakage diode appears in Figs. 1.35 and 1.36. This example would represent the expanded list of data and characteristics. The term *rectifier* is applied to a diode when it is frequently used in a *rectification* process to be described in Chapter 2.

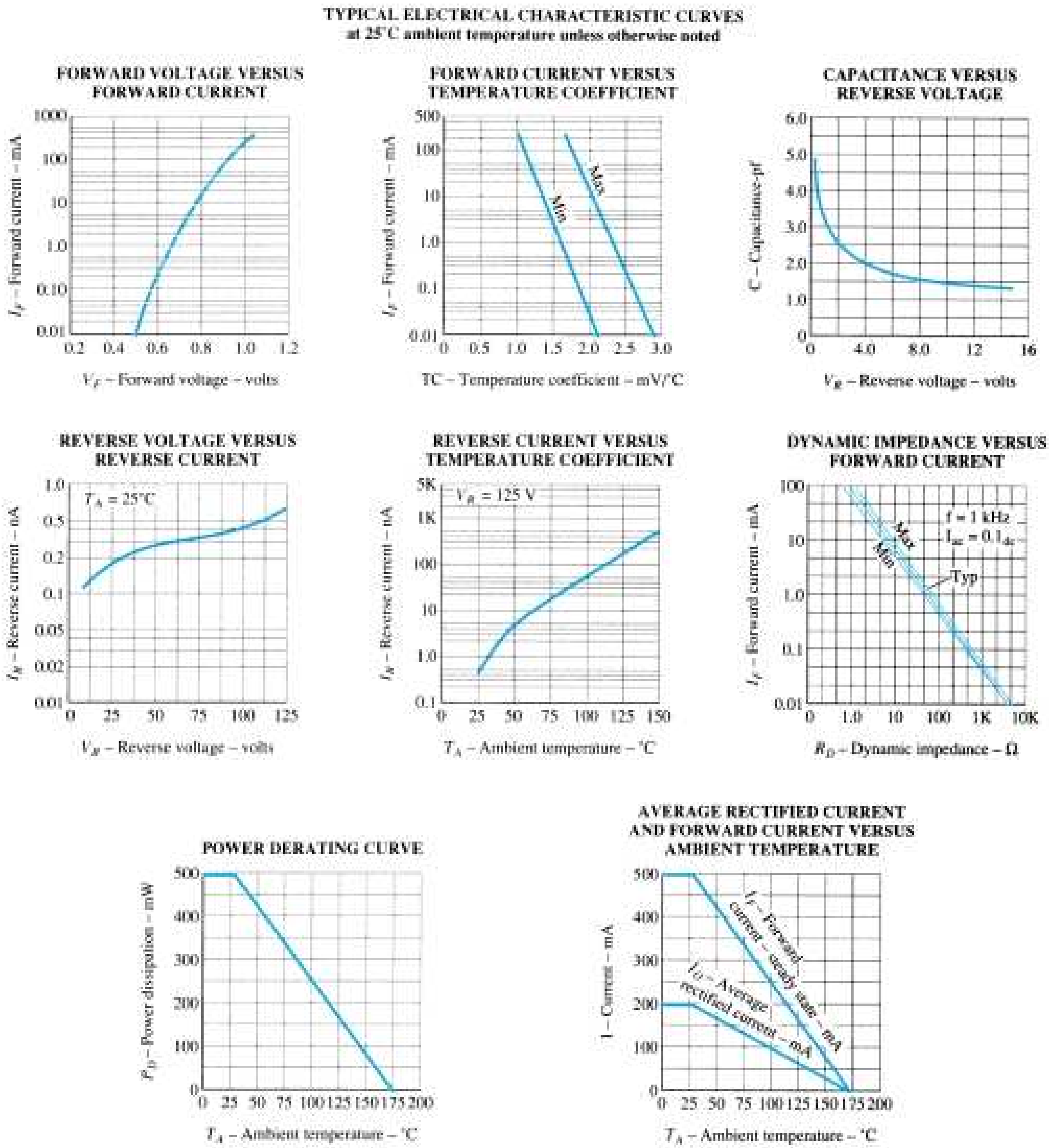


Figure 1.36 Terminal characteristics of a high-voltage diode.

Specific areas of the specification sheet have been highlighted in blue with a letter identification corresponding with the following description:

A: The *minimum* reverse-bias voltage (PIVs) for a diode at a specified reverse saturation current.

B: Temperature characteristics as indicated. Note the use of the Celsius scale and the wide range of utilization [recall that 32°F = 0°C = freezing (H_2O) and 212°F = 100°C = boiling (H_2O)].

C: Maximum power dissipation level $P_D = V_D I_D = 500$ mW. The maximum power rating decreases at a rate of 3.33 mW per degree increase in temperature above room temperature (25°C), as clearly indicated by the *power derating curve* of Fig. 1.36.

D: Maximum continuous forward current $I_{F_{max}} = 500$ mA (note I_F versus temperature in Fig. 1.36).

E: Range of values of V_F at $I_F = 200$ mA. Note that it exceeds $V_T = 0.7$ V for both devices.

F: Range of values of V_F at $I_F = 1.0$ mA. Note in this case how the upper limits surround 0.7 V.

G: At $V_R = 20$ V and a typical operating temperature $I_R = 500$ nA $= 0.5$ μA, while at a higher reverse voltage I_R drops to 5 nA $= 0.005$ μA.

H: The capacitance level between terminals is about 8 pF for the diode at $V_R = V_D = 0$ V (no-bias) and an applied frequency of 1 MHz.

I: The reverse recovery time is 3 μs for the list of operating conditions.

A number of the curves of Fig. 1.36 employ a log scale. A brief investigation of Section 11.2 should help with the reading of the graphs. Note in the top left figure how V_F increased from about 0.5 V to over 1 V as I_F increased from 10 μA to over 100 mA. In the figure below we find that the reverse saturation current does change slightly with increasing levels of V_R but remains at less than 1 nA at room temperature up to $V_R = 125$ V. As noted in the adjoining figure, however, note how quickly the reverse saturation current increases with increase in temperature (as forecasted earlier).

In the top right figure note how the capacitance decreases with increase in reverse-bias voltage, and in the figure below note that the ac resistance (r_d) is only about 1 Ω at 100 mA and increases to 100 Ω at currents less than 1 mA (as expected from the discussion of earlier sections).

The average rectified current, peak repetitive forward current, and peak forward surge current as they appear on the specification sheet are defined as follows:

1. *Average rectified current.* A half-wave-rectified signal (described in Section 2.8) has an average value defined by $I_{av} = 0.318 I_{peak}$. The average current rating is lower than the continuous or peak repetitive forward currents because a half-wave current waveform will have instantaneous values much higher than the average value.
2. *Peak repetitive forward current.* This is the maximum instantaneous value of repetitive forward current. Note that since it is at this level for a brief period of time, its level can be higher than the continuous level.
3. *Peak forward surge current.* On occasion during turn-on, malfunctions, and so on, there will be very high currents through the device for very brief intervals of time (that are not repetitive). This rating defines the maximum value and the time interval for such surges in current level.

The more one is exposed to specification sheets, the "friendlier" they will become, especially when the impact of each parameter is clearly understood for the application under investigation.

1.10 TRANSITION AND DIFFUSION CAPACITANCE

Electronic devices are inherently sensitive to very high frequencies. Most shunt capacitive effects that can be ignored at lower frequencies because the reactance $X_C = 1/2\pi fC$ is very large (open-circuit equivalent). This, however, cannot be ignored at very high frequencies. X_C will become sufficiently small due to the high value of f to introduce a low-reactance "shorting" path. In the *p-n* semiconductor diode, there are two capacitive effects to be considered. Both types of capacitance are present in the forward- and reverse-bias regions, but one so outweighs the other in each region that we consider the effects of only one in each region.

> *In the reverse-bias region we have the transition- or depletion-region capacitance (C_T), while in the forward-bias region we have the diffusion (C_D) or storage capacitance.*

Recall that the basic equation for the capacitance of a parallel-plate capacitor is defined by $C = \epsilon A/d$, where ϵ is the permittivity of the dielectric (insulator) between the plates of area A separated by a distance d. In the reverse-bias region there is a depletion region (free of carriers) that behaves essentially like an insulator between the layers of opposite charge. Since the depletion width (d) will increase with increased reverse-bias potential, the resulting transition capacitance will decrease, as shown in Fig. 1.37. The fact that the capacitance is dependent on the applied reverse-bias potential has application in a number of electronic systems. In fact, in Chapter 20 a diode will be introduced whose operation is wholly dependent on this phenomenon.

Although the effect described above will also be present in the forward-bias region, it is overshadowed by a capacitance effect directly dependent on the rate at which charge is injected into the regions just outside the depletion region. The result is that increased levels of current will result in increased levels of diffusion capacitance. However, increased levels of current result in reduced levels of associated resistance (to be demonstrated shortly), and the resulting time constant ($\tau = RC$), which is very important in high-speed applications, does not become excessive.

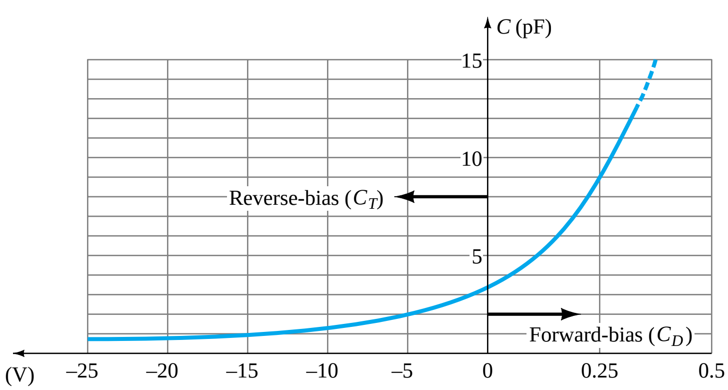


Figure 1.37 Transition and diffusion capacitance versus applied bias for a silicon diode.

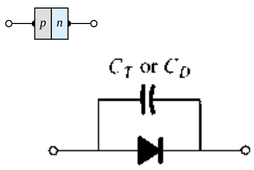


Figure 1.38 Including the effect of the transition or diffusion capacitance on the semiconductor diode.

The capacitive effects described above are represented by a capacitor in parallel with the ideal diode, as shown in Fig. 1.38. For low- or mid-frequency applications (except in the power area), however, the capacitor is normally not included in the diode symbol.

1.11 REVERSE RECOVERY TIME

There are certain pieces of data that are normally provided on diode specification sheets provided by manufacturers. One such quantity that has not been considered yet is the reverse recovery time, denoted by t_{rr}. In the forward-bias state it was shown earlier that there are a large number of electrons from the *n*-type material progressing through the *p*-type material and a large number of holes in the *n*-type—a requirement for conduction. The electrons in the *p*-type and holes progressing through the *n*-type material establish a large number of minority carriers in each material. If the applied voltage should be reversed to establish a reverse-bias situation, we would ideally like to see the diode change instantaneously from the conduction state to the nonconduction state. However, because of the large number of minority carriers in each material, the diode current will simply reverse as shown in Fig. 1.39 and stay at this measurable level for the period of time t_s (storage time) required for the minority carriers to return to their majority-carrier state in the opposite material. In essence, the diode will remain in the short-circuit state with a current I_{reverse} determined by the network parameters. Eventually, when this storage phase has passed, the current will reduce in level to that associated with the nonconduction state. This second period of time is denoted by t_t (transition interval). The reverse recovery time is the sum of these two intervals: $t_{rr} = t_s + t_t$. Naturally, it is an important consideration in high-speed switching applications. Most commercially available switching diodes have a t_{rr} in the range of a few nanoseconds to 1 μs. Units are available, however, with a t_{rr} of only a few hundred picoseconds (10^{-12}).

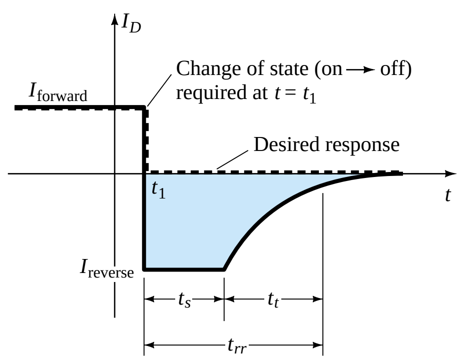


Figure 1.39 Defining the reverse recovery time.

1.12 SEMICONDUCTOR DIODE NOTATION

The notation most frequently used for semiconductor diodes is provided in Fig. 1.40. For most diodes any marking such as a dot or band, as shown in Fig. 1.40, appears at the cathode end. The terminology anode and cathode is a carryover from vacuum-tube notation. The anode refers to the higher or positive potential, and the cathode refers to the lower or negative terminal. This combination of bias levels will result in a forward-bias or "on" condition for the diode. A number of commercially available semiconductor diodes appear in Fig. 1.41. Some details of the actual construction of devices such as those appearing in Fig. 1.41 are provided in Chapters 12 and 20.

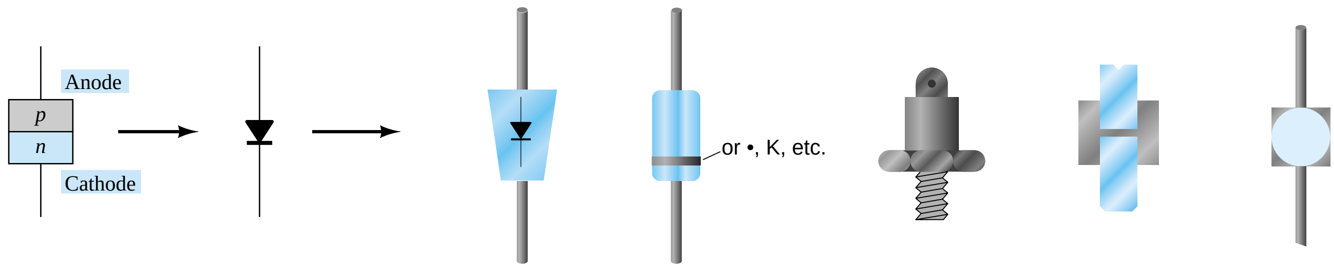


Figure 1.40 Semiconductor diode notation.

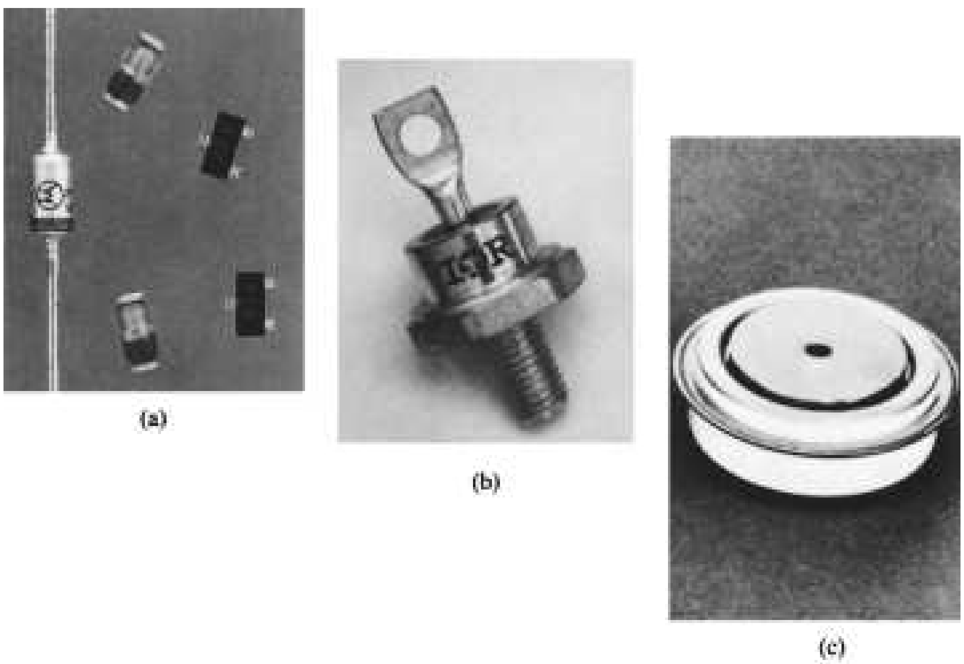


Figure 1.41 Various types of junction diodes. [(a) Courtesy of Motorola Inc.; and (b) and (c) Courtesy International Rectifier Corporation.]

1.13 DIODE TESTING

The condition of a semiconductor diode can be determined quickly using (1) a digital display meter (DDM) with a *diode checking function*, (2) the *ohmmeter section* of a multimeter, or (3) a *curve tracer.*

Diode Checking Function

A digital display meter with a diode checking capability appears in Fig. 1.42. Note the small diode symbol as the bottom option of the rotating dial. When set in this position and hooked up as shown in Fig. 1.43a, the diode should be in the “on” state and the display will provide an indication of the forward-bias voltage such as 0.67 V (for Si). The meter has an internal constant current source (about 2 mA) that will define the voltage level as indicated in Fig. 1.43b. An OL indication with the hookup of Fig. 1.43a reveals an open (defective) diode. If the leads are reversed, an OL indication should result due to the expected open-circuit equivalence for the diode. In general, therefore, an OL indication in both directions is an indication of an open or defective diode.

Figure 1.42 Digital display meter with diode checking capability. (Courtesy Computronics Technology, Inc.)

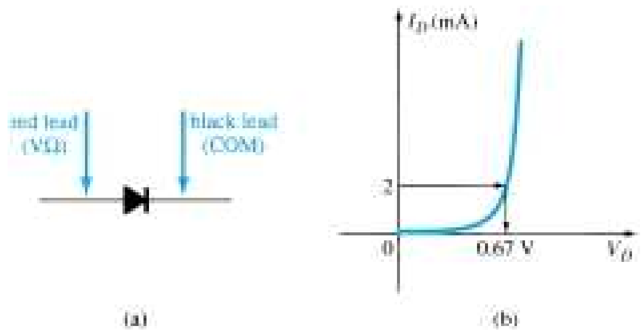


Figure 1.43 Checking a diode in the forward-bias state.

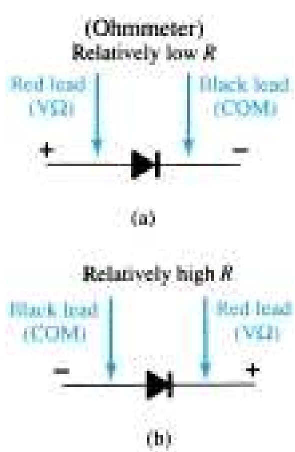


Figure 1.44 Checking a diode with an ohmmeter.

Ohmmeter Testing

In Section 1.7 we found that the forward-bias resistance of a semiconductor diode is quite low compared to the reverse-bias level. Therefore, if we measure the resistance of a diode using the connections indicated in Fig. 1.44a, we can expect a relatively low level. The resulting ohmmeter indication will be a function of the current established through the diode by the internal battery (often 1.5 V) of the ohmmeter circuit. The higher the current, the less the resistance level. For the reverse-bias situation the reading should be quite high, requiring a high resistance scale on the meter, as indicated in Fig. 1.44b. A high resistance reading in both directions obviously indicates an open (defective device) condition, while a very low resistance reading in both directions will probably indicate a shorted device.

Curve Tracer

The curve tracer of Fig. 1.45 can display the characteristics of a host of devices, including the semiconductor diode. By properly connecting the diode to the test panel at the bottom center of the unit and adjusting the controls, the display of Fig. 1.46

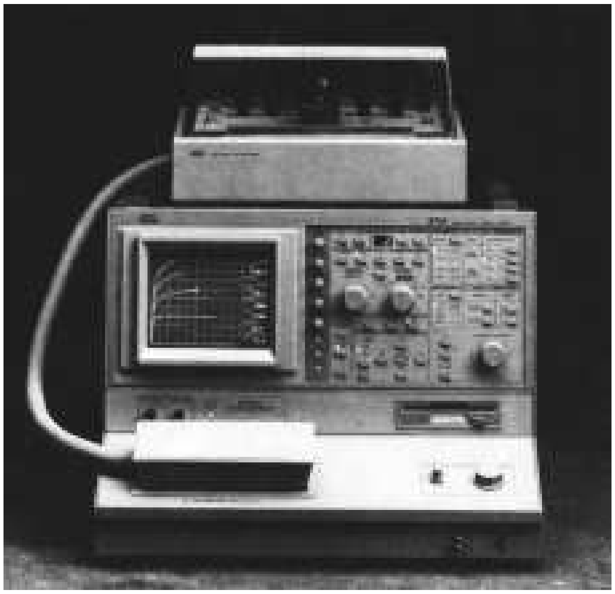


Figure 1.45 Curve tracer. (Courtesy of Tektronix, Inc.)

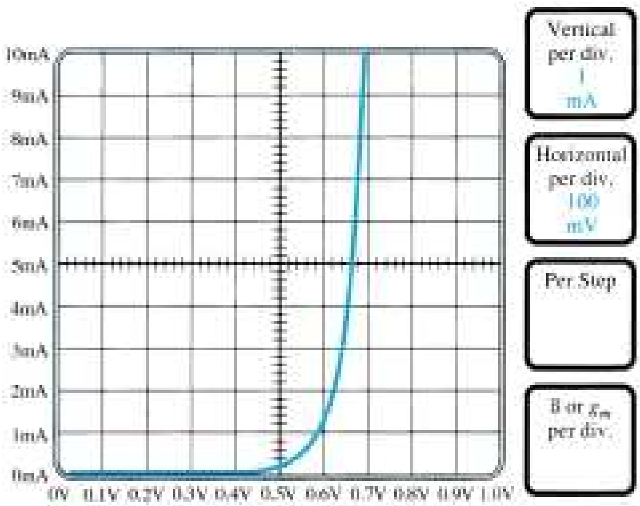


Figure 1.46 Curve tracer response to 1N4007 silicon diode.

can be obtained. Note that the vertical scaling is 1 mA/div, resulting in the levels indicated. For the horizontal axis the scaling is 100 mV/div, resulting in the voltage levels indicated. For a 2-mA level as defined for a DDM, the resulting voltage would be about 625 mV = 0.625 V. Although the instrument initially appears quite complex, the instruction manual and a few moments of exposure will reveal that the desired results can usually be obtained without an excessive amount of effort and time. The same instrument will appear on more than one occasion in the chapters to follow as we investigate the characteristics of the variety of devices.

1.14 ZENER DIODES

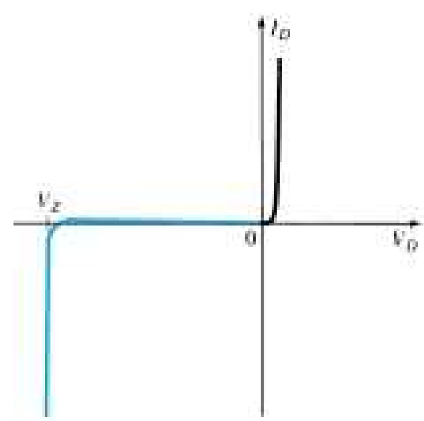


Figure 1.47 Reviewing the Zener region.

The Zener region of Fig. 1.47 was discussed in some detail in Section 1.6. The characteristic drops in an almost vertical manner at a reverse-bias potential denoted V_Z. The fact that the curve drops down and away from the horizontal axis rather than up and away for the positive V_D region reveals that the current in the Zener region has a direction opposite to that of a forward-biased diode.

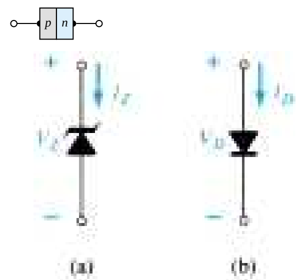


Figure 1.48 Conduction direction: (a) Zener diode; (b) semiconductor diode.

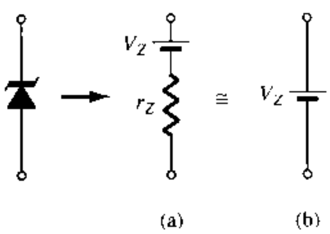


Figure 1.49 Zener equivalent circuit: (a) complete; (b) approximate.

This region of unique characteristics is employed in the design of *Zener diodes,* which have the graphic symbol appearing in Fig. 1.48a. Both the semiconductor diode and zener diode are presented side by side in Fig. 1.48 to ensure that the direction of conduction of each is clearly understood together with the required polarity of the applied voltage. For the semiconductor diode the "on" state will support a current in the direction of the arrow in the symbol. For the Zener diode the direction of conduction is opposite to that of the arrow in the symbol as pointed out in the introduction to this section. Note also that the polarity of V_D and V_Z are the same as would be obtained if each were a resistive element.

The location of the Zener region can be controlled by varying the doping levels. An increase in doping, producing an increase in the number of added impurities, will decrease the Zener potential. Zener diodes are available having Zener potentials of 1.8 to 200 V with power ratings from $\frac{1}{4}$ to 50 W. Because of its higher temperature and current capability, silicon is usually preferred in the manufacture of Zener diodes.

The complete equivalent circuit of the Zener diode in the Zener region includes a small dynamic resistance and dc battery equal to the Zener potential, as shown in Fig. 1.49. For all applications to follow, however, we shall assume as a first approximation that the external resistors are much larger in magnitude than the Zener-equivalent resistor and that the equivalent circuit is simply the one indicated in Fig. 1.49b.

A larger drawing of the Zener region is provided in Fig. 1.50 to permit a description of the Zener nameplate data appearing in Table 1.4 for a 10-V, 500-mW, 20% diode. The term *nominal* associated with V_Z indicates that it is a typical average value. Since this is a 20% diode, the Zener potential can be expected to vary as 10 V ± 20%

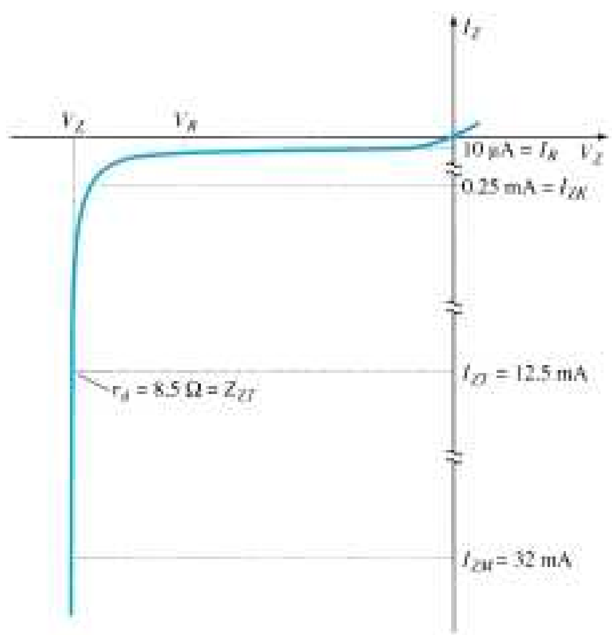


Figure 1.50 Zener test characteristics.

TABLE 1.4 **Electrical Characteristics (25°C Ambient Temperature Unless Otherwise Noted)**

Zener Voltage Nominal, V_Z *(V)*	*Test Current,* I_{ZT} *(mA)*	*Max Dynamic Impedance,* Z_{ZT} *at* I_{ZT} *(Ω)*	*Maximum Knee Impedance,* Z_{ZK} *at* I_{ZK} *(Ω) (mA)*	*Maximum Reverse Current,* I_R *at* V_R *(μA)*	*Test Voltage,* V_R *(V)*	*Maximum Regulator Current,* I_{ZM} *(mA)*	*Typical Temperature Coefficient (%/°C)*
10	12.5	8.5	700 0.25	10	7.2	32	+0.072

or from 8 to 12 V in its range of application. Also available are 10% and 5% diodes with the same specifications. The test current I_{ZT} is the current defined by the $\frac{1}{4}$ power level, and Z_{ZT} is the dynamic impedance at this current level. The maximum knee impedance occurs at the knee current of I_{ZK}. The reverse saturation current is provided at a particular potential level, and I_{ZM} is the maximum current for the 20% unit.

The temperature coefficient reflects the percent change in V_Z with temperature. It is defined by the equation

$$T_C = \frac{\Delta V_Z}{V_Z(T_1 - T_0)} \times 100\% \qquad \%/°C \qquad (1.12)$$

where ΔV_Z is the resulting change in Zener potential due to the temperature variation. Note in Fig. 1.51a that the temperature coefficient can be positive, negative, or even zero for different Zener levels. A positive value would reflect an increase in V_Z with an increase in temperature, while a negative value would result in a decrease in value with increase in temperature. The 24-V, 6.8-V, and 3.6-V levels refer to three Zener diodes having these nominal values within the same family of Zeners. The curve for the 10-V Zener would naturally lie between the curves of the 6.8-V and 24-V devices. Returning to Eq. (1.12), T_0 is the temperature at which V_Z is provided (normally room temperature—25°C), and T_1 is the new level. Example 1.3 will demonstrate the use of Eq. (1.12).

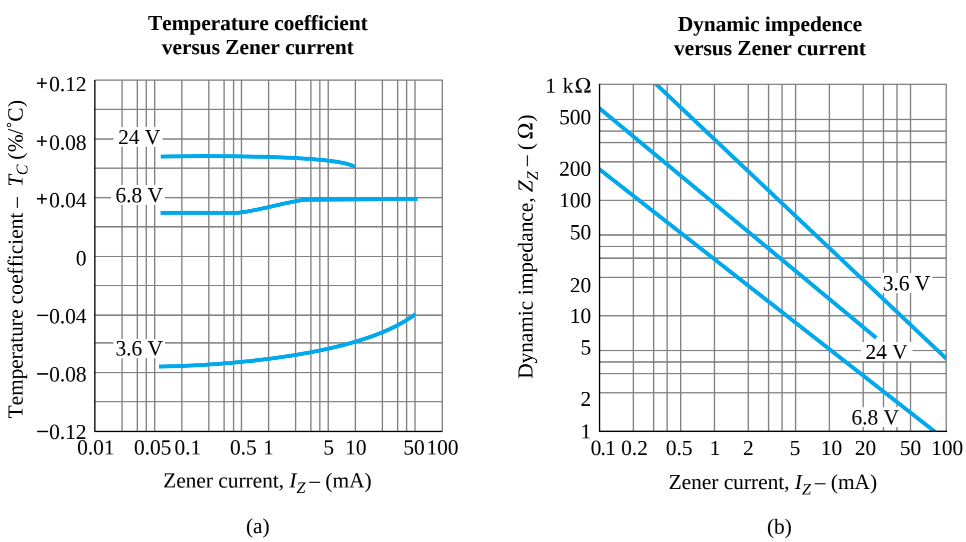


Figure 1.51 Electrical characteristics for a 10-V, 500-mW Zener diode.

EXAMPLE 1.3

Determine the nominal voltage for the Zener diode of Table 1.4 at a temperature of 100°C.

Solution

From Eq. 1.12,

$$\Delta V_Z = \frac{T_C V_Z}{100}(T_1 - T_0)$$

Substitution values from Table 1.4 yield

$$\Delta V_Z = \frac{(0.072)(10\text{ V})}{100}(100°\text{C} - 25°\text{C})$$
$$= (0.0072)(75)$$
$$= 0.54\text{ V}$$

and because of the positive temperature coefficient, the new Zener potential, defined by V'_Z, is

$$V'_Z = V_Z + 0.54\text{ V}$$
$$\mathbf{= 10.54\ V}$$

The variation in dynamic impedance (fundamentally, its series resistance) with current appears in Fig. 1.51b. Again, the 10-V Zener appears between the 6.8-V and 24-V Zeners. Note that the heavier the current (or the farther up the vertical rise you are in Fig. 1.47), the less the resistance value. Also note that as you drop below the knee of the curve, the resistance increases to significant levels.

The terminal identification and the casing for a variety of Zener diodes appear in Fig. 1.52. Figure 1.53 is an actual photograph of a variety of Zener devices. Note that their appearance is very similar to the semiconductor diode. A few areas of application for the Zener diode will be examined in Chapter 2.

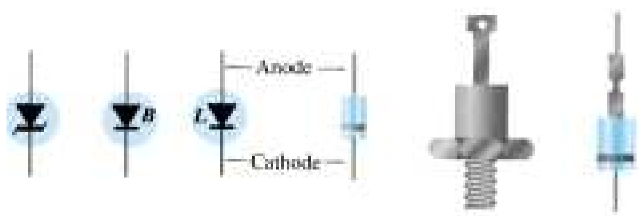


Figure 1.52 Zener terminal identification and symbols.

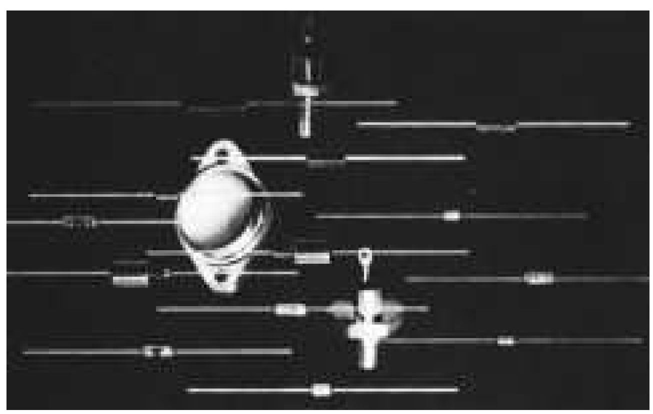


Figure 1.53 Zener diodes. (Courtesy Siemens Corporation.)

1.15 LIGHT-EMITTING DIODES

The increasing use of digital displays in calculators, watches, and all forms of instrumentation has contributed to the current extensive interest in structures that will emit light when properly biased. The two types in common use today to perform this function are the *light-emitting diode* (LED) and the *liquid-crystal display* (LCD). Since the LED falls within the family of *p-n* junction devices and will appear in some of the networks in the next few chapters, it will be introduced in this chapter. The LCD display is described in Chapter 20.

As the name implies, the light-emitting diode (LED) is a diode that will give off visible light when it is energized. In any forward-biased *p-n* junction there is, within the structure and primarily close to the junction, a recombination of holes and electrons. This recombination requires that the energy possessed by the unbound free electron be transferred to another state. In all semiconductor *p-n* junctions some of this energy will be given off as heat and some in the form of photons. In silicon and germanium the greater percentage is given up in the form of heat and the emitted light is insignificant. In other materials, such as gallium arsenide phosphide (GaAsP) or gallium phosphide (GaP), the number of photons of light energy emitted is sufficient to create a very visible light source.

The process of giving off light by applying an electrical source of energy is called electroluminescence.

As shown in Fig. 1.54 with its graphic symbol, the conducting surface connected to the *p*-material is much smaller, to permit the emergence of the maximum number of photons of light energy. Note in the figure that the recombination of the injected carriers due to the forward-biased junction results in emitted light at the site of recombination. There may, of course, be some absorption of the packages of photon energy in the structure itself, but a very large percentage are able to leave, as shown in the figure.

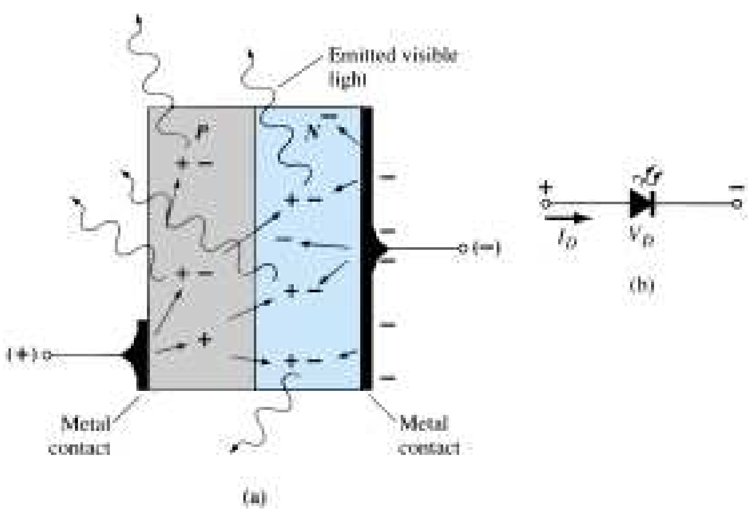
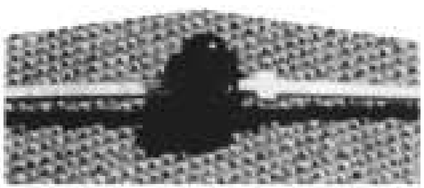


Figure 1.54 (a) Process of electroluminescence in the LED; (b) graphic symbol.

The appearance and characteristics of a subminiature high-efficiency solid-state lamp manufactured by Hewlett-Packard appears in Fig. 1.55. Note in Fig. 1.55b that the peak forward current is 60 mA, with 20 mA the typical average forward current. The test conditions listed in Fig. 1.55c, however, are for a forward current of 10 mA. The level of V_D under forward-bias conditions is listed as V_F and extends from 2.2 to 3 V. In other words, one can expect a typical operating current of about 10 mA at 2.5 V for good light emission.

Two quantities yet undefined appear under the heading Electrical/Optical Characteristics at $T_A = 25°C$. They are the *axial luminous intensity* (I_V) and the *luminous efficacy* (η_v). Light intensity is measured in *candela.* One candela emits a light flux of 4π lumens and establishes an illumination of 1 footcandle on a 1-ft^2 area 1 ft from the light source. Even though this description may not provide a clear understanding of the candela as a unit of measure, its level can certainly be compared between similar devices. The term *efficacy* is, by definition, a measure of the ability of a device to produce a desired effect. For the LED this is the ratio of the number of lumens generated per applied watt of electrical energy. The relative efficiency is defined by the luminous intensity per unit current, as shown in Fig. 1.55g. The relative intensity of each color versus wavelength appears in Fig. 1.55d.

Since the LED is a *p-n* junction device, it will have a forward-biased characteristic (Fig. 1.55e) similar to the diode response curves. Note the almost linear increase in relative luminous intensity with forward current (Fig. 1.55f). Figure 1.55h reveals that the longer the pulse duration at a particular frequency, the lower the permitted peak current (after you pass the break value of t_p). Figure 1.55i simply reveals that the intensity is greater at 0° (or head on) and the least at 90° (when you view the device from the side).



(a)

Absolute Maximum Ratings at T_A = 25°C

Parameter	*High Eff. Red 4160*	*Units*
Power dissipation	120	mW
Average forward current	20[1]	mA
Peak forward current	60	mA
Operating and storage temperature range	−55°C to 100°C	
Lead soldering temperature [1.6 mm (0.063 in.) from body]	230°C for 3 seconds	

[1] Derate from 50°C at 0.2 mA/°C.

(b)

Electrical/Optical Characteristics at T_A = 25°C

Symbol	*Description*	*High Eff. Red 4160 Min.*	*Typ.*	*Max.*	*Units*	*Test Conditions*
I_V	Axial luminous intensity	1.0	3.0		mcd	I_F = 10 mA
$2\theta_{1/2}$	Included angle between half luminous intensity points		80		deg.	Note 1
λ_{peak}	Peak wavelength		635		nm	Measurement at peak
λ_d	Dominant wavelength		628		nm	Note 2
τ_s	Speed of response		90		ns	
C	Capacitance		11		pF	V_F = 0; f = 1 Mhz
θ_{JC}	Thermal resistance		120		°C/W	Junction to cathode lead at 0.79 mm (.031 in) from body
V_F	Forward voltage		2.2	3.0	V	I_F = 10 mA
BV_R	Reverse breakdown voltage	5.0			V	I_R = 100 µA
η_v	Luminous efficacy		147		lm/W	Note 3

NOTES:
1. $\theta_{1/2}$ is the off-axis angle at which the luminous intensity is half the axial luminous intensity.
2. The dominant wavelength, λ_d, is derived from the CIE chromaticity diagram and represents the single wavelength that defines the color of the device.
3. Radiant intensity, I_e, in watts/steradian, may be found from the equation $I_e = I_v/\eta_v$, where I_v is the luminous intensity in candelas and η_v is the luminous efficacy in lumens/watt.

(c)

Figure 1.55 Hewlett-Packard subminiature high-efficiency red solid-state lamp: (a) appearance; (b) absolute maximum ratings; (c) electrical/optical characteristics; (d) relative intensity versus wavelength; (e) forward current versus forward voltage; (f) relative luminous intensity versus forward current; (g) relative efficiency versus peak current; (h) maximum peak current versus pulse duration; (i) relative luminous intensity versus angular displacement. (Courtesy Hewlett-Packard Corporation.)

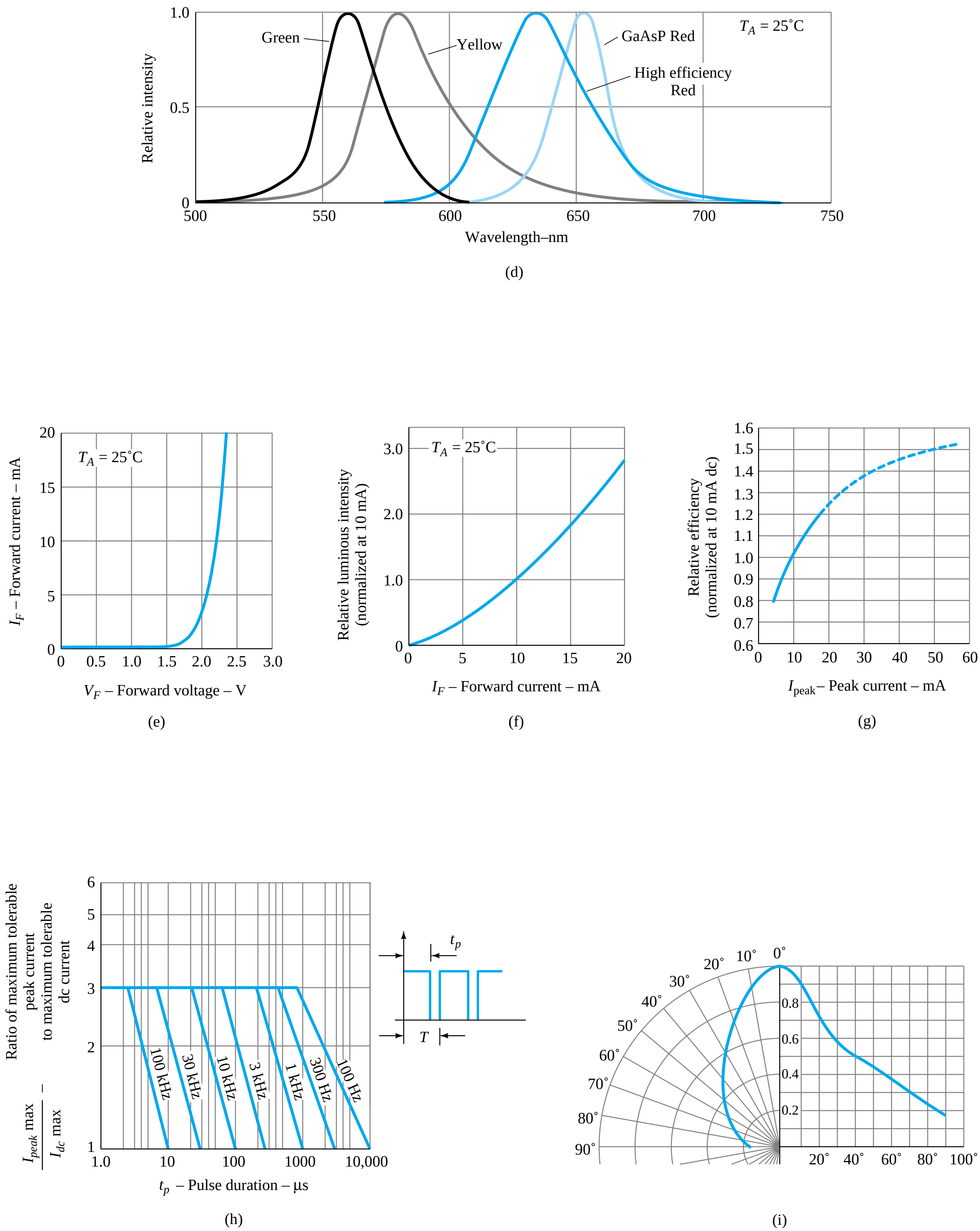


Figure 1.55 Continued.

LED displays are available today in many different sizes and shapes. The light-emitting region is available in lengths from 0.1 to 1 in. Numbers can be created by segments such as shown in Fig. 1.56. By applying a forward bias to the proper *p*-type material segment, any number from 0 to 9 can be displayed.

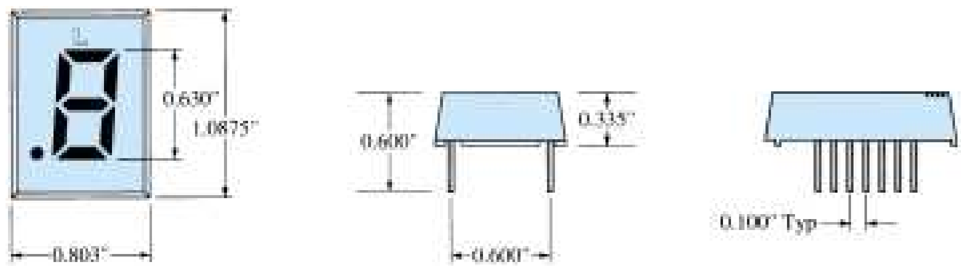


Figure 1.56 Litronix segment display.

There are also two-lead LED lamps that contain two LEDs, so that a reversal in biasing will change the color from green to red, or vice versa. LEDs are presently available in red, green, yellow, orange, and white, and white with blue soon to be commercially available. In general, LEDs operate at voltage levels from 1.7 to 3.3 V, which makes them completely compatible with solid-state circuits. They have a fast response time (nanoseconds) and offer good contrast ratios for visibility. The power requirement is typically from 10 to 150 mW with a lifetime of 100,000+ hours. Their semiconductor construction adds a significant ruggedness factor.

1.16 DIODE ARRAYS—INTEGRATED CIRCUITS

The unique characteristics of integrated circuits will be introduced in Chapter 12. However, we have reached a plateau in our introduction to electronic circuits that permits at least a surface examination of diode arrays in the integrated-circuit package. You will find that the integrated circuit is not a unique device with characteristics totally different from those we examine in these introductory chapters. It is simply a packaging technique that permits a significant reduction in the size of electronic systems. In other words, internal to the integrated circuit are systems and discrete devices that were available long before the integrated circuit as we know it today became a reality.

One possible array appears in Fig. 1.57. Note that eight diodes are internal to the diode array. That is, in the container shown in Fig. 1.58 there are diodes set in a single silicon wafer that have all the anodes connected to pin 1 and the cathodes of each to pins 2 through 9. Note in the same figure that pin 1 can be determined as being to the left of the small projection in the case if we look from the bottom toward the case. The other numbers then follow in sequence. If only one diode is to be used, then only pins 1 and 2 (or any number from 3 to 9) would be used. The remaining diodes would be left hanging and not affect the network to which pins 1 and 2 are connected.

Another diode array appears in Fig. 1.59 (see page 44). In this case the package is different but the numbering sequence appears in the outline. Pin 1 is the pin directly above the small indentation as you look down on the device.

PLANAR AIR–ISOLATED MONOLITHIC DIODE ARRAY

- **C . . . 5.0 pF (MAX)**
- **ΔV_F . . . 15 mv (MAX) @ 10 mA**

ABSOLUTE MAXIMUM RATINGS (Note 1)

Temperatures

Storage Temperature Range	–55°C to +200°C
Maximum Junction Operating Temperature	+150°C
Lead Temperature	+260°C

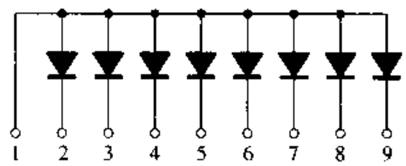
Power Dissipation (Note 2)

Maximum Dissipation per Junction at 25°C Ambient	400 mW
per Package at 25°C Ambient	600 mW
Linear Derating Factor (from 25°C) Junction	3.2 mW/°C
Package	4.8 mW/°C

Maximum Voltage and Currents

WIV	Working Inverse Voltage	55 V
I_F	Continuous Forward Current	350 mA
$i_{f(surge)}$	Peak Forward Surge Current	
	Pulse Width = 1.0 s	1.0 A
	Pulse Width = 1.0 μs	2.0 A

CONNECTION DIAGRAM



See Package Outline TO-96

ELECTRICAL CHARACTERISTICS (25°C Ambient Temperature unless otherwise noted)

SYMBOL	CHARACTERISTIC	MIN	MAX	UNITS	TEST CONDITIONS
B_V	Breakdown Voltage	60		V	$I_R = 10\ \mu A$
V_F	Forward Voltage (Note 3)		1.5 1.1 1.0	V V V	$I_F = 500$ mA $I_F = 200$ mA $I_F = 100$ mA
I_R	Reverse Current Reverse Current ($T_A = 150°C$)		100 100	nA μA	$V_R = 40$ V $V_R = 40$ V
C	Capacitance		5.0	pF	$V_R = 0$, f = 1 MHz
V_{FM}	Peak Forward Voltage		4.0	V	$I_f = 500$ mA, $t_r < 10$ ns
t_{fr}	Forward Recovery Time		40	ns	$I_f = 500$ mA, $t_r < 10$ ns
t_{rr}	Reverse Recovery Time		10 50	ns ns	$I_f = I_r = 10 - 200$ mA $R_L = 100\Omega$, Rec. to 0.1 I_r $I_f = 500$ mA, $I_r = 50$ mA $R_L = 100\Omega$, Rec. to 5 mA
ΔV_F	Forward Voltage Match		15	mV	$I_F = 10$ mA

NOTES
1 These ratings are limiting values above which life or satisfactory performance may be impaired.
2 These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operation.
3 V_F is measured using an 8 ms pulse.

Figure 1.57 Monolithic diode array.

1.17 PSPICE WINDOWS

The computer has now become such an integral part of the electronics industry that the capabilities of this working "tool" must be introduced at the earliest possible opportunity. For those students with no prior computer experience there is a common initial fear of this seemingly complicated powerful system. With this in mind the computer analysis of this book was designed to make the computer system more "friendly" by revealing the relative ease with which it can be applied to perform some very help-

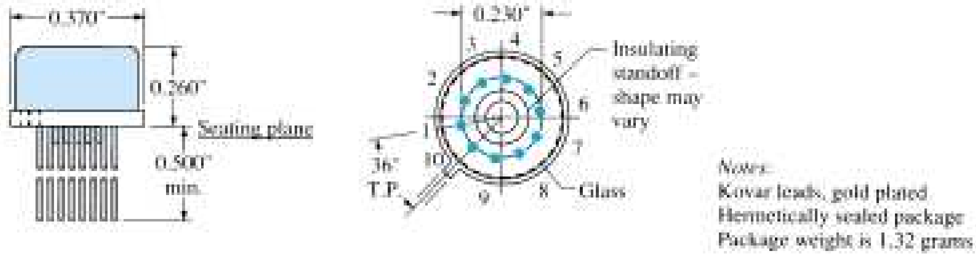


Figure 1.58 Package outline TO-96 for a diode array. All dimensions are in inches.

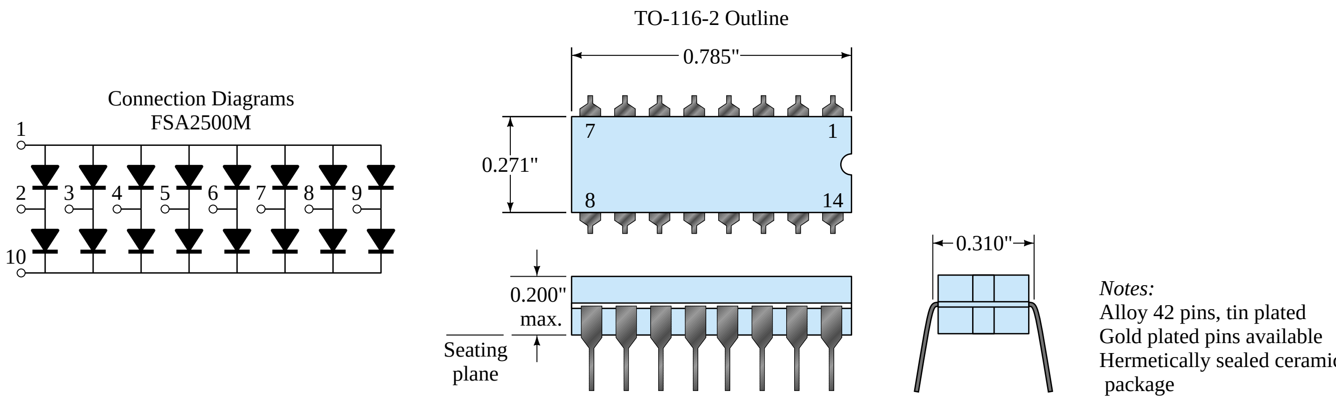


Figure 1.59 Monolithic diode array. All dimensions are in inches.

ful and special tasks in a minimum amount of time with a high degree of accuracy. The content was written with the assumption that the reader has no prior computer experience or exposure to the terminology to be applied. There is also no suggestion that the content of this book is sufficient to permit a complete understanding of the "hows" and "whys" that will surface. The purpose here is solely to introduce some of the terminology, discuss a few of its capabilities, reveal the possibilities available, touch on some of its limitations, and demonstrate its versatility with a number of carefully chosen examples.

In general, the computer analysis of electronic systems can take one of two approaches: using a *language* such as BASIC, Fortran, Pascal, or C; or utilizing a *software package* such as PSpice, MicroCap II, Breadboard, or Circuit Master, to name a few. A language, through its symbolic notation, forms a bridge between the user and the computer that permits a dialogue between the two for establishing the operations to be performed.

In earlier editions of this text, the chosen language was BASIC, primarily because it uses a number of familiar words and phrases from the English language that in themselves reveal the operation to be performed. When a language is employed to analyze a system, a *program* is developed that sequentially defines the operations to be performed—in much the same order in which we perform the same analysis in longhand. As with the longhand approach, one wrong step and the result obtained can be completely meaningless. Programs typically develop with time and application as more efficient paths toward a solution become obvious. Once established in its "best" form it can be cataloged for future use. The important advantage of the language approach is that a program can be tailored to meet all the special needs of the user. It permits innovative "moves" by the user that can result in printouts of data in an informative and interesting manner.

The alternative approach referred to above utilizes a software package to perform the desired investigation. A software package is a program written and tested over a period of time designed to perform a particular type of analysis or synthesis in an efficient manner with a high level of accuracy.

The package itself cannot be altered by the user, and its application is limited to the operations built into the system. A user must adjust his or her desire for output information to the range of possibilities offered by the package. In addition, the user must input information exactly as requested by the package or the data may be misinterpreted. The software package chosen for this book is PSpice.* PSpice currently is available in two forms: DOS and Windows. Although DOS format was the first introduced, the Windows version is the most popular today. The Windows version employed in this text is 8.0, the latest available. A photograph of a complete Design Center package appears in Fig. 1.60 with the 8.0 CD-ROM version. It is also available in 3.5″ diskettes. A more sophisticated version referred to simply as SPICE is finding widespread application in industry.

Figure 1.60 PSpice Design package. (Courtesy of the OrCAD-MicroSim Corporation.)

In total, therefore, a software package is "packaged" to perform a specific series of calculations and operations and to provide the results in a defined format. A language permits an expanded level of flexibility but also fails to benefit from the extensive testing and research normally devoted to the development of a "trusted" package. The user must define which approach best fits the needs of the moment. Obviously, if a package exists for the desired analysis or synthesis, it should be considered before turning to the many hours required to develop a reliable, efficient program. In addition, one may acquire the data needed for a particular analysis from a software package and then turn to a language to define the format of the output. In many ways, the two approaches go hand in hand. If one is to depend on computer analysis on a continuing basis, knowledge of the use and limits of both languages and software packages is a necessity. The choice of which language or software package to become familiar with is primarily a function of the area of investigation. Fortunately, however, a fluent knowledge of one language or a particular software package will usually help the user become familiar with other languages and software packages. There is a similarity in purpose and procedures that ease the transition from one approach to another.

When using PSpice Windows, the network is first drawn on the screen followed by an analysis dictated by the needs of the user. This text will be using **Version 8.0,** though the differences between this and earlier Windows versions are so few and relatively minor for this level of application that one should not be concerned if using an earlier edition. The first step, of course, is to install PSpice into the hard-disk

*PSpice is a registered trademark of the OrCAD-MicroSim Corporation.

memory of your computer following the directions provided by MicroSim. Next, the **Schematics** screen must be obtained using a control mechanism such as **Windows 95.** Once established, the elements for the network must be obtained and placed on the screen to build the network. In this text, the procedure for each element will be described following the discussion of the characteristics and analysis of each device.

Since we have just finished covering the diode in detail, the procedure for finding the diodes stored in the library will be introduced along with the method for placing them on the screen. The next chapter will introduce the procedure for analyzing a complete network with diodes using PSpice. There are several ways to proceed, but the most direct path is to click on the picture symbol with the binoculars on the top right of the schematics screen. As you bring the marker close to the box using the mouse, a message **Get New Part** will be displayed. Left click on the symbol and a **Part Browser Basic** dialog box will appear. By choosing **Libraries,** a **Library Browser** dialog box will appear and the **EVAL.slb** library should be chosen. When selected, all available parts in this library will appear in the **Part** listing. Next, scroll the **Part** list and choose the **D1N4148** diode. The result is that the **Part Name** will appear above and the **Description** will indicate it is a diode. Once set, click **OK** and the **Part Browser Basic** dialog box will reappear with the full review of the chosen element. To place the device on the screen and close the dialog box, simply click on the **Place & Close** option. The result is that the diode will appear on the screen and can be put in place with a left click of the mouse. Once located, two labels will appear—one indicating how any diodes have been placed (**D1, D2, D3,** and so on) and the other the name of the chosen diode (**D1N4148**). The same diode can be placed in other places on the same screen by simply moving the pointer and left clicking the mouse. The process can be ended by a single right click of the mouse. Any of the diodes can be removed by simply clicking on them to make them red and pressing the **Delete** key. If preferred, the **Edit** choice of the menu bar at the top of the screen also can be chosen, followed by using the **Delete** command.

Another path for obtaining an element is to choose **Draw** on the menu bar, followed by **Get New Part.** Once chosen, the **Part Browser Basic** dialog box will appear as before and the same procedure can be followed. Now that we know the D1N4148 diode exists, it can be obtained directly once the **Part Browser Basic** dialog box appears. Simply type D1N4148 in the **Part Name** box, followed by **Place & Close,** and the **diode** will appear on the screen.

If a diode has to be moved, simply left click on it once, until it turns red. Then, click on it again and hold the clicker down on the mouse. At the same time, move the diode to any location you prefer and, when set, lift up on the clicker. Remember that anything in red can be operated on. To remove the red status, simply remove the pointer from the element and click it once. The diode will turn green and blue, indicating that its location and associated information is set in memory. For all the above and for the chapters to follow, if you happen to have a monochromatic (black-and-white) screen, you will simply have to remember whether the device is in the active state.

If the label or parameters of the diode are to be changed, simply click on the element once (to make it red) and choose **Edit,** followed by **Model.** An **Edit Model** dialog box will appear with a choice of changing the **model reference** (D1N4148), the **text** associated with each parameter, or the **parameters** that define the characteristics of the diode.

As mentioned above, additional comments regarding use of the diode will be made in the chapters to follow. For the moment, we are at least aware of how to find and place an element on the screen. If time permits, review the other elements available within the various libraries to prepare yourself for the work to follow.

PROBLEMS

§ 1.2 Ideal Diode

1. Describe in your own words the meaning of the word *ideal* as applied to a device or system.

2. Describe in your own words the characteristics of the *ideal* diode and how they determine the on and off states of the device. That is, describe why the short-circuit and open-circuit equivalents are appropriate.

3. What is the one important difference between the characteristics of a simple switch and those of an ideal diode?

§ 1.3 Semiconductor Materials

4. In your own words, define *semiconductor, resistivity, bulk resistance,* and *ohmic contact resistance.*

5. (a) Using Table 1.1, determine the resistance of a silicon sample having an area of 1 cm^2 and a length of 3 cm.

(b) Repeat part (a) if the length is 1 cm and the area 4 cm^2.

(c) Repeat part (a) if the length is 8 cm and the area 0.5 cm^2.

(d) Repeat part (a) for copper and compare the results.

6. Sketch the atomic structure of copper and discuss why it is a good conductor and how its structure is different from germanium and silicon.

7. In your own words, define an intrinsic material, a negative temperature coefficient, and covalent bonding.

8. Consult your reference library and list three materials that have a negative temperature coefficient and three that have a positive temperature coefficient.

§ 1.4 Energy Levels

9. How much energy in joules is required to move a charge of 6 C through a difference in potential of 3 V?

10. If 48 eV of energy is required to move a charge through a potential difference of 12 V, determine the charge involved.

11. Consult your reference library and determine the level of E_g for GaP and ZnS, two semiconductor materials of practical value. In addition, determine the written name for each material.

§ 1.5 Extrinsic Materials—*n*- and *p*-Type

12. Describe the difference between *n*-type and *p*-type semiconductor materials.

13. Describe the difference between donor and acceptor impurities.

14. Describe the difference between majority and minority carriers.

15. Sketch the atomic structure of silicon and insert an impurity of arsenic as demonstrated for silicon in Fig. 1.9.

16. Repeat Problem 15 but insert an impurity of indium.

17. Consult your reference library and find another explanation of hole versus electron flow. Using both descriptions, describe in your own words the process of hole conduction.

§ 1.6 Semiconductor Diode

18. Describe in your own words the conditions established by forward- and reverse-bias conditions on a *p-n* junction diode and how the resulting current is affected.

19. Describe how you will remember the forward- and reverse-bias states of the *p-n* junction diode. That is, how you will remember which potential (positive or negative) is applied to which terminal?

20. Using Eq. (1.4), determine the diode current at 20°C for a silicon diode with I_s = 50 nA and an applied forward bias of 0.6 V.

21. Repeat Problem 20 for $T = 100°C$ (boiling point of water). Assume that I_s has increased to 5.0 μA.

22. (a) Using Eq. (1.4), determine the diode current at 20°C for a silicon diode with $I_s = 0.1\ \mu A$ at a reverse-bias potential of -10 V.
 (b) Is the result expected? Why?

23. (a) Plot the function $y = e^x$ for x from 0 to 5.
 (b) What is the value of $y = e^x$ at $x = 0$?
 (c) Based on the results of part (b), why is the factor -1 important in Eq. (1.4)?

24. In the reverse-bias region the saturation current of a silicon diode is about 0.1 μA ($T = 20°C$). Determine its approximate value if the temperature is increased 40°C.

25. Compare the characteristics of a silicon and a germanium diode and determine which you would prefer to use for most practical applications. Give some details. Refer to a manufacturer's listing and compare the characteristics of a germanium and a silicon diode of similar maximum ratings.

26. Determine the forward voltage drop across the diode whose characteristics appear in Fig. 1.24 at temperatures of $-75°C$, 25°C, 100°C, and 200°C and a current of 10 mA. For each temperature, determine the level of saturation current. Compare the extremes of each and comment on the ratio of the two.

§ 1.7 Resistance Levels

27. Determine the static or dc resistance of the commercially available diode of Fig. 1.19 at a forward current of 2 mA.

28. Repeat Problem 26 at a forward current of 15 mA and compare results.

29. Determine the static or dc resistance of the commercially available diode of Fig. 1.19 at a reverse voltage of -10 V. How does it compare to the value determined at a reverse voltage of -30 V?

30. (a) Determine the dynamic (ac) resistance of the diode of Fig. 1.29 at a forward current of 10 mA using Eq. (1.6).
 (b) Determine the dynamic (ac) resistance of the diode of Fig. 1.29 at a forward current of 10 mA using Eq. (1.7).
 (c) Compare solutions of parts (a) and (b).

31. Calculate the dc and ac resistance for the diode of Fig. 1.29 at a forward current of 10 mA and compare their magnitudes.

32. Using Eq. (1.6), determine the ac resistance at a current of 1 mA and 15 mA for the diode of Fig. 1.29. Compare the solutions and develop a general conclusion regarding the ac resistance and increasing levels of diode current.

33. Using Eq. (1.7), determine the ac resistance at a current of 1 mA and 15 mA for the diode of Fig. 1.19. Modify the equation as necessary for low levels of diode current. Compare to the solutions obtained in Problem 32.

34. Determine the average ac resistance for the diode of Fig. 1.19 for the region between 0.6 and 0.9 V.

35. Determine the ac resistance for the diode of Fig. 1.19 at 0.75 V and compare to the average ac resistance obtained in Problem 34.

§ 1.8 Diode Equivalent Circuits

36. Find the piecewise-linear equivalent circuit for the diode of Fig. 1.19. Use a straight line segment that intersects the horizontal axis at 0.7 V and best approximates the curve for the region greater than 0.7 V.

37. Repeat Problem 36 for the diode of Fig. 1.29.

§ 1.9 Diode Specification Sheets

***38.** Plot I_F versus V_F using linear scales for the diode of Fig. 1.36. Note that the provided graph employs a log scale for the vertical axis (log scales are covered in sections 11.2 and 11.3).

39. Comment on the change in capacitance level with increase in reverse-bias potential for the diode of Fig. 1.36.

40. Does the reverse saturation current of the diode of Fig. 1.36 change significantly in magnitude for reverse-bias potentials in the range -25 to -100 V?

***41.** For the diode of Fig. 1.36 determine the level of I_R at room temperature (25°C) and the boiling point of water (100°C). Is the change significant? Does the level just about double for every 10°C increase in temperature?

42. For the diode of Fig. 1.36 determine the maximum ac (dynamic) resistance at a forward current of 0.1, 1.5, and 20 mA. Compare levels and comment on whether the results support conclusions derived in earlier sections of this chapter.

43. Using the characteristics of Fig. 1.36, determine the maximum power dissipation levels for the diode at room temperature (25°C) and 100°C. Assuming that V_F remains fixed at 0.7 V, how has the maximum level of I_F changed between the two temperature levels?

44. Using the characteristics of Fig. 1.36, determine the temperature at which the diode current will be 50% of its value at room temperature (25°C).

§ 1.10 Transition and Diffusion Capacitance

***45.** (a) Referring to Fig. 1.37, determine the transition capacitance at reverse-bias potentials of -25 and -10 V. What is the ratio of the change in capacitance to the change in voltage?

(b) Repeat part (a) for reverse-bias potentials of -10 and -1 V. Determine the ratio of the change in capacitance to the change in voltage.

(c) How do the ratios determined in parts (a) and (b) compare? What does it tell you about which range may have more areas of practical application?

46. Referring to Fig. 1.37, determine the diffusion capacitance at 0 and 0.25 V.

47. Describe in your own words how diffusion and transition capacitances differ.

48. Determine the reactance offered by a diode described by the characteristics of Fig. 1.37 at a forward potential of 0.2 V and a reverse potential of -20 V if the applied frequency is 6 MHz.

§ 1.11 Reverse Recovery Time

49. Sketch the waveform for i of the network of Fig. 1.61 if $t_t = 2t_s$ and the total reverse recovery time is 9 ns.

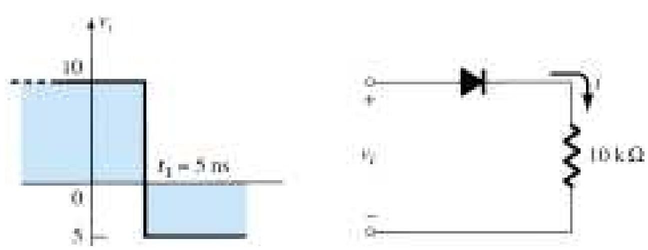


Figure 1.61 Problem 49

§ 1.14 Zener Diodes

50. The following characteristics are specified for a particular Zener diode: $V_Z = 29$ V, $V_R = 16.8$ V, $I_{ZT} = 10$ mA, $I_R = 20\ \mu$A, and $I_{ZM} = 40$ mA. Sketch the characteristic curve in the manner displayed in Fig. 1.50.

***51.** At what temperature will the 10-V Zener diode of Fig. 1.50 have a nominal voltage of 10.75 V? (*Hint:* Note the data in Table 1.4.)

52. Determine the temperature coefficient of a 5-V Zener diode (rated 25°C value) if the nominal voltage drops to 4.8 V at a temperature of 100°C.

53. Using the curves of Fig. 1.51a, what level of temperature coefficient would you expect for a 20-V diode? Repeat for a 5-V diode. Assume a linear scale between nominal voltage levels and a current level of 0.1 mA.

54. Determine the dynamic impedance for the 24-V diode at $I_Z = 10$ mA for Fig. 1.51b. Note that it is a log scale.

*55. Compare the levels of dynamic impedance for the 24-V diode of Fig. 1.51b at current levels of 0.2, 1, and 10 mA. How do the results relate to the shape of the characteristics in this region?

§ 1.15 Light-Emitting Diodes

56. Referring to Fig. 1.55e, what would appear to be an appropriate value of V_T for this device? How does it compare to the value of V_T for silicon and germanium?

57. Using the information provided in Fig. 1.55, determine the forward voltage across the diode if the relative luminous intensity is 1.5.

*58. (a) What is the percent increase in relative efficiency of the device of Fig. 1.55 if the peak current is increased from 5 to 10 mA?

(b) Repeat part (a) for 30 to 35 mA (the same increase in current).

(c) Compare the percent increase from parts (a) and (b). At what point on the curve would you say there is little gained by further increasing the peak current?

*59. (a) Referring to Fig. 1.55h, determine the maximum tolerable peak current if the period of the pulse duration is 1 ms, the frequency is 300 Hz, and the maximum tolerable dc current is 20 mA.

(b) Repeat part (a) for a frequency of 100 Hz.

60. (a) If the luminous intensity at 0° angular displacement is 3.0 mcd for the device of Fig. 1.55, at what angle will it be 0.75 mcd?

(b) At what angle does the loss of luminous intensity drop below the 50% level?

*61. Sketch the current derating curve for the average forward current of the high-efficiency red LED of Fig. 1.55 as determined by temperature. (Note the absolute maximum ratings.)

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*Please Note: Asterisks indicate more difficult problems.