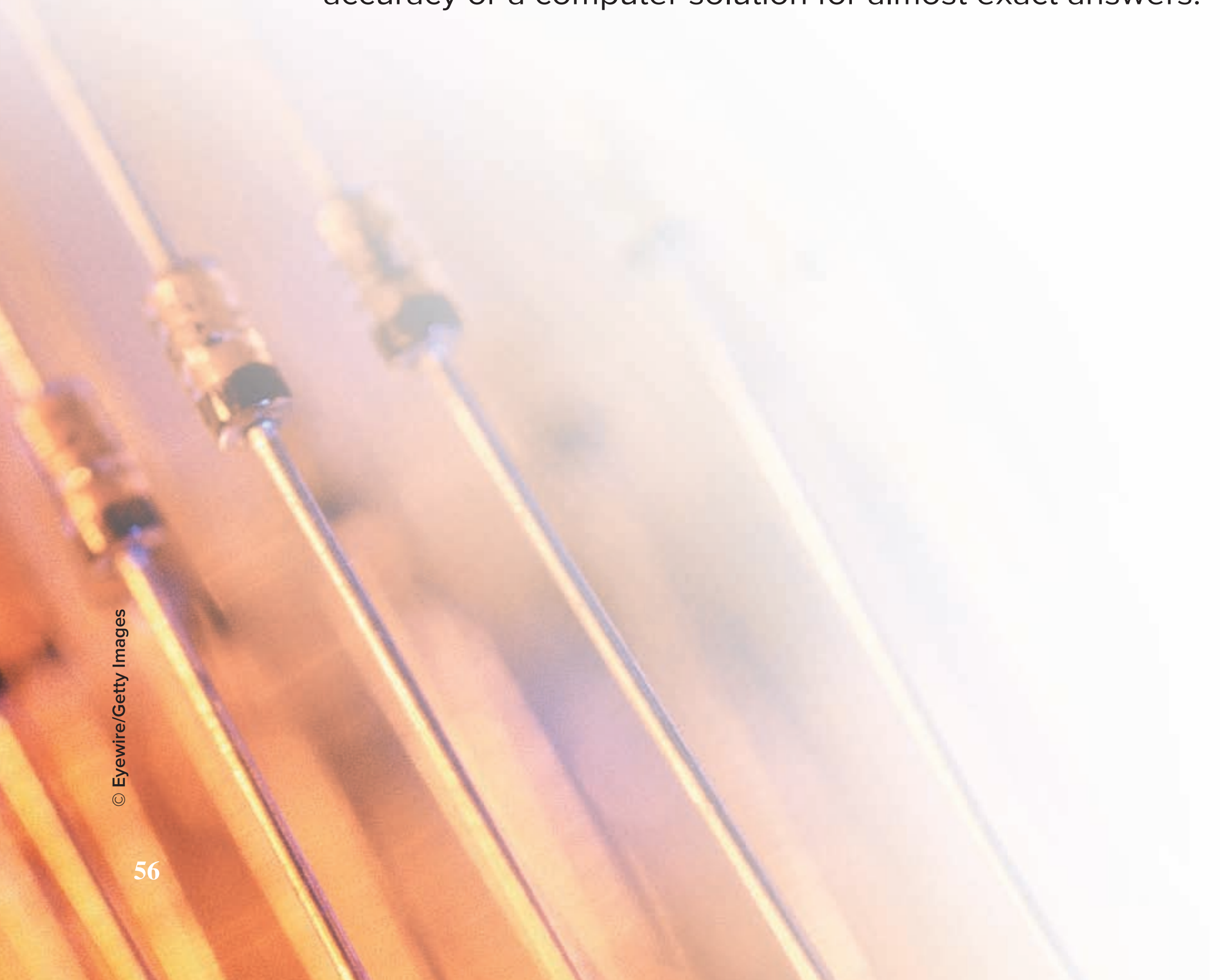
chapter 3

Diode Theory

This chapter continues our study of diodes. After discussing the diode curve, we look at approximations of a diode. We need approximations because exact analysis is tedious and time consuming in most situations. For instance, an ideal approximation is usually adequate for troubleshooting, and a second approximation gives quick and easy solutions in many cases. Beyond this, we can use a third approximation for better accuracy or a computer solution for almost exact answers.



© Eyewire/Getty Images

Objectives

After studying this chapter, you should be able to:

- Draw a diode symbol and label the anode and cathode.
- Draw a diode curve and label all significant points and areas.
- Describe the ideal diode.
- Describe the second approximation.
- Describe the third approximation.
- List four basic characteristics of diodes shown on a data sheet.
- Describe how to test a diode using a DMM and VOM.
- Describe the relationship between components, circuits, and systems.

Chapter Outline

Vocabulary

anode	ideal diode	maximum forward current
bulk resistance	knee voltage	nonlinear device
cathode	linear device	ohmic resistance
electronic systems	load line	power rating

3-1 Basic Ideas

An ordinary resistor is a **linear device** because the graph of its current versus voltage is a straight line. A diode is different. It is a **nonlinear device** because the graph of its current versus voltage is not a straight line. The reason is the barrier potential. When the diode voltage is less than the barrier potential, the diode current is small. When the diode voltage exceeds the barrier potential, the diode current increases rapidly.

The Schematic Symbol and Case Styles

Figure 3-1*a* shows the *pn* structure and schematic symbol of a diode. The *p* side is called the **anode,** and the *n* side the **cathode.** The diode symbol looks like an arrow that points from the *p* side to the *n* side, from the anode to the cathode. Figure 3-1*b* shows some of the many typical diode case styles. Many, but not all, diodes have the cathode lead (K) identified by a colored band.

Basic Diode Circuit

Figure 3-1*c* shows a diode circuit. In this circuit, the diode is forward biased. How do we know? Because the positive battery terminal drives the *p* side through a resistor, and the negative battery terminal is connected to the *n* side. With this connection, the circuit is trying to push holes and free electrons toward the junction.

In more complicated circuits, it may be difficult to decide whether the diode is forward biased. Here is a guideline. Ask yourself this question: Is the external circuit pushing current in the *easy direction* of flow? If the answer is yes, the diode is forward biased.

What is the easy direction of flow? If you use conventional current, the easy direction is the same direction as the diode arrow. If you prefer electron flow, the easy direction is the other way.

Figure 3-1 Diode. (*a*) Schematic symbol; (*b*) diode case styles; (*c*) forward bias.

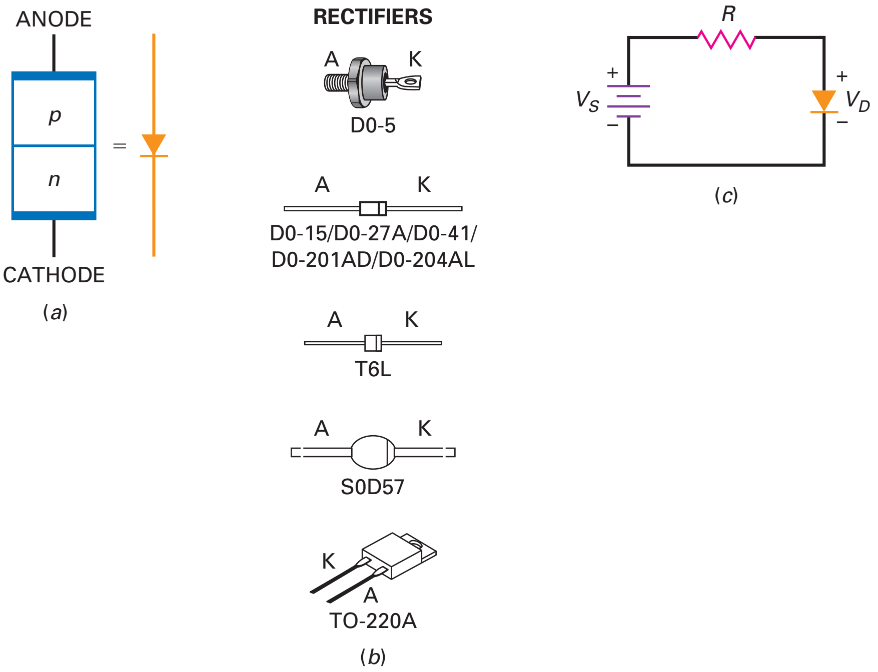
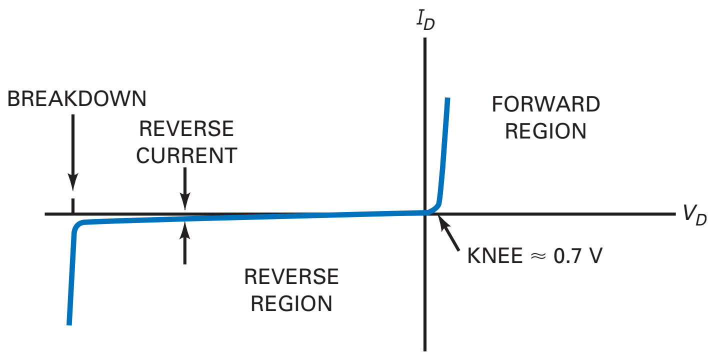


Figure 3-2 Diode curve.



When the diode is part of a complicated circuit, we also can use Thevenin's theorem to determine whether it is forward biased. For instance, assume that we have reduced a complicated circuit with Thevenin's theorem to get Fig. 3-1*c*. We would know that the diode is forward biased.

The Forward Region

Figure 3-1*c* is a circuit that you can set up in the laboratory. After you connect this circuit, you can measure the diode current and voltage. You can also reverse the polarity of the dc source and measure diode current and voltage for reverse bias. If you plot the diode current versus the diode voltage, you will get a graph that looks like Fig. 3-2.

This is a visual summary of the ideas discussed in the preceding chapter. For instance, when the diode is forward biased, there is no significant current until the diode voltage is greater than the barrier potential. On the other hand, when the diode is reverse biased, there is almost no reverse current until the diode voltage reaches the breakdown voltage. Then, avalanche produces a large reverse current, destroying the diode.

Knee Voltage

In the forward region, the voltage at which the current starts to increase rapidly is called the **knee voltage** of the diode. The knee voltage equals the barrier potential. Analysis of diode circuits usually comes down to determining whether the diode voltage is more or less than the knee voltage. If it's more, the diode conducts easily. If it's less, the diode conducts poorly. We define the knee voltage of a silicon diode as:

$$V_K \approx 0.7 \text{ V} \tag{3-1}$$

(*Note:* The symbol ≈ means "approximately equal to.")

Even though germanium diodes are rarely used in new designs, you may still encounter germanium diodes in special circuits or in older equipment. For this reason, remember that the knee voltage of a germanium diode is approximately 0.3 V. This lower knee voltage is an advantage and accounts for the use of a germanium diode in certain applications.

GOOD TO KNOW

Special purpose diodes, such as the Schottky diode, have replaced the germanium diode in modern applications requiring low knee voltages.

Bulk Resistance

Above the knee voltage, the diode current increases rapidly. This means that small increases in the diode voltage cause large increases in diode current. After the barrier potential is overcome, all that impedes the current is the **ohmic resistance** of the *p* and *n* regions. In other words, if the *p* and *n* regions were two separate pieces of semiconductor, each would have a resistance that you could measure with an ohmmeter, the same as an ordinary resistor.

The sum of the ohmic resistances is called the **bulk resistance** of the diode. It is defined as:

$$R_B = R_P + R_N \tag{3-2}$$

The bulk resistance depends on the size of the *p* and *n* regions and how heavily doped they are. Often, the bulk resistance is less than 1 Ω.

Maximum DC Forward Current

If the current in a diode is too large, the excessive heat can destroy the diode. For this reason, a manufacturer's data sheet specifies the maximum current a diode can safely handle without shortening its life or degrading its characteristics.

The **maximum forward current** is one of the maximum ratings given on a data sheet. This current may be listed as I_{max}, $I_{F(max)}$, I_O, etc., depending on the manufacturer. For instance, a 1N456 has a maximum forward current rating of 135 mA. This means that it can safely handle a continuous forward current of 135 mA.

Power Dissipation

You can calculate the power dissipation of a diode the same way as you do for a resistor. It equals the product of diode voltage and current. As a formula:

$$P_D = V_D I_D \tag{3-3}$$

The **power rating** is the maximum power the diode can safely dissipate without shortening its life or degrading its properties. In symbols, the definition is:

$$P_{max} = V_{max} I_{max} \tag{3-4}$$

where V_{max} is the voltage corresponding to I_{max}. For instance, if a diode has a maximum voltage and current of 1 V and 2 A, its power rating is 2 W.

Example 3-1

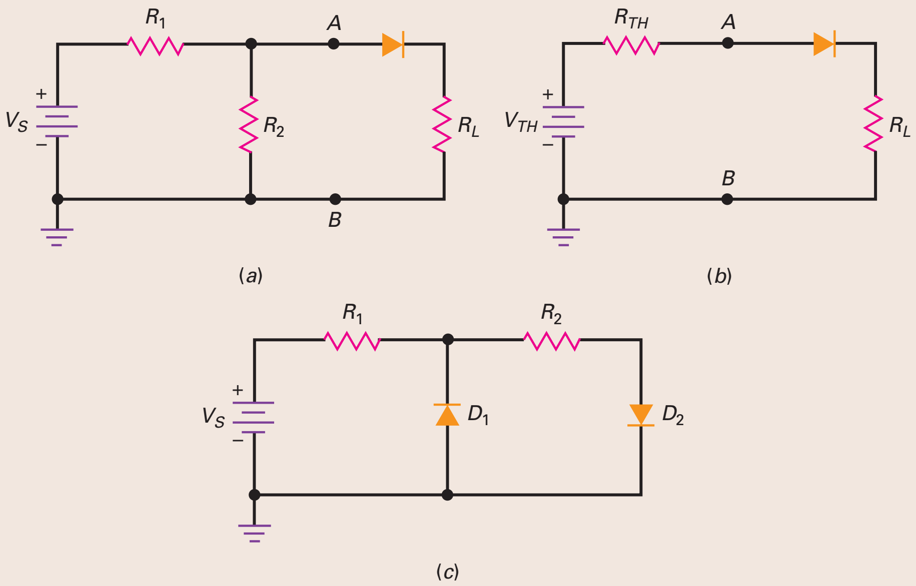
Multisim

Is the diode of Fig. 3-3*a* forward biased or reverse biased?

SOLUTION The voltage across R_2 is positive; therefore, the circuit is trying to push current in the easy direction of flow. If this is not clear, visualize the Thevenin circuit facing the diode as shown in Fig. 3-3*b*. In order to determine the Thevenin equivalent, remember that $V_{TH} = \frac{R_2}{R_1 + R_2}(V_S)$ and $R_{TH} = \frac{R_1}{R_2}$. In this series circuit, you can see that the dc source is trying to push current in the easy direction of flow. Therefore, the diode is forward biased.

Whenever in doubt, reduce the circuit to a series circuit. Then, it will be clear whether the dc source is trying to push current in the easy direction or not.

Figure 3-3



PRACTICE PROBLEM 3-1 Are the diodes of Fig. 3-3*c* forward biased or reverse biased?

Example 3-2

A diode has a power rating of 5 W. If the diode voltage is 1.2 V and the diode current is 1.75 A, what is the power dissipation? Will the diode be destroyed?

SOLUTION

$$P_D = (1.2 \text{ V})(1.75 \text{ A}) = 2.1 \text{ W}$$

This is less than the power rating, so the diode will not be destroyed.

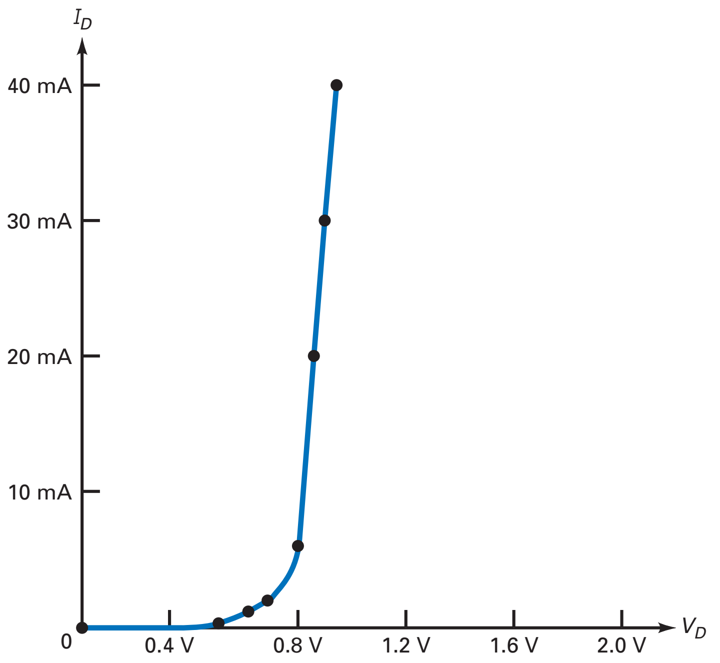
PRACTICE PROBLEM 3-2 Referring to Example 3-2, what is the diode's power dissipation if the diode voltage is 1.1 V and the diode current is 2 A?

3-2 The Ideal Diode

Figure 3-4 shows a detailed graph of the forward region of a diode. Here you see the diode current I_D versus diode voltage V_D. Notice how the current is approximately zero until the diode voltage approaches the barrier potential. Somewhere in the vicinity of 0.6 to 0.7 V, the diode current increases. When the diode voltage is greater than 0.8 V, the diode current is significant and the graph is almost linear.

Depending on how a diode is doped and its physical size, it may differ from other diodes in its maximum forward current, power rating, and other characteristics. If we need an exact solution, we have to use the graph of the

Figure 3-4 Graph of forward current.



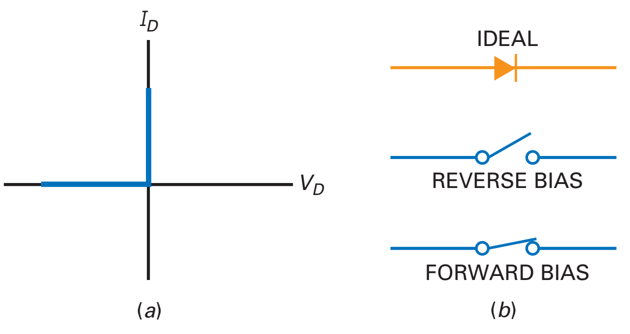
particular diode. Although the exact current and voltage points will differ from one diode to the next, the graph of any diode is similar to Fig. 3-4. All silicon diodes have a knee voltage of approximately 0.7 V.

Most of the time, we do not need an exact solution. This is why we can and should use approximations for a diode. We will begin with the simplest approximation, called an **ideal diode.** In the most basic terms, what does a diode do? It conducts well in the forward direction and poorly in the reverse direction. Ideally, a diode acts like a perfect conductor (zero resistance) when forward biased and like a perfect insulator (infinite resistance) when reverse biased.

Figure 3-5*a* shows the current-voltage graph of an ideal diode. It echoes what we just said: zero resistance when forward biased and infinite resistance when reverse biased. It is impossible to build such a device, but this is what manufacturers would produce if they could.

Is there any device that acts like an ideal diode? Yes. An ordinary switch has zero resistance when closed and infinite resistance when open. Therefore, an ideal diode acts like a switch that closes when forward biased and opens when reverse biased. Figure 3-5*b* summarizes the switch idea.

Figure 3-5 (*a*) Ideal diode curve; (*b*) ideal diode acts like a switch.



Example 3-3

Use the ideal diode to calculate the load voltage and load current in Fig. 3-6*a*.

SOLUTION Since the diode is forward biased, it is equivalent to a closed switch. Visualize the diode as a closed switch. Then, you can see that all of the source voltage appears across the load resistor:

$$V_L = 10\text{ V}$$

With Ohm's law, the load current is:

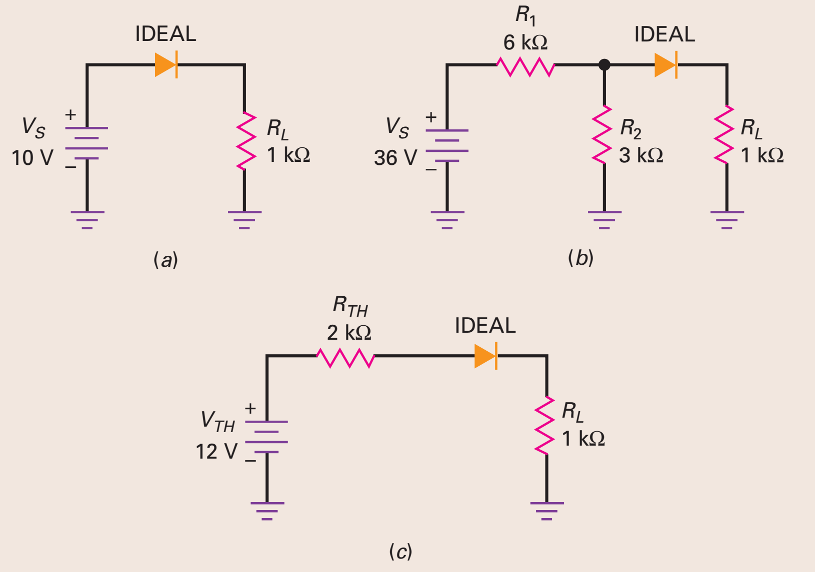
$$I_L = \frac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

PRACTICE PROBLEM 3-3 In Fig. 3-6*a*, find the ideal load current if the source voltage is 5 V.

Example 3-4

Calculate the load voltage and load current in Fig. 3-6*b* using an ideal diode.

Figure 3-6



SOLUTION One way to solve this problem is to Thevenize the circuit to the left of the diode. Looking from the diode back toward the source, we see a voltage divider with 6 kΩ and 3 kΩ. The Thevenin voltage is 12 V, and the Thevenin resistance is 2 kΩ. Figure 3-6*c* shows the Thevenin circuit driving the diode.

Now that we have a series circuit, we can see that the diode is forward biased. Visualize the diode as a closed switch. Then, the remaining calculations are:

$$I_L = \frac{12\text{ V}}{3\text{ k}\Omega} = 4\text{ mA}$$

and

$$V_L = (4\text{ mA})(1\text{ k}\Omega) = 4\text{ V}$$

You don't have to use Thevenin's theorem. You can analyze Fig. 3-6*b* by visualizing the diode as a closed switch. Then, you have 3 kΩ in parallel with 1 kΩ, equivalent to 750 Ω. Using Ohm's law, you can calculate a voltage drop of 32 V across the 6 kΩ. The rest of the analysis produces the same load voltage and load current.

PRACTICE PROBLEM 3-4 Using Fig. 3-6*b*, change the 36 V source to 18 V and solve for the load voltage and load current using an ideal diode.

3-3 The Second Approximation

GOOD TO KNOW

When you troubleshoot a circuit that contains a silicon diode that is supposed to be forward biased, a diode voltage measurement much greater than 0.7 V means that the diode has failed and is, in fact, open.

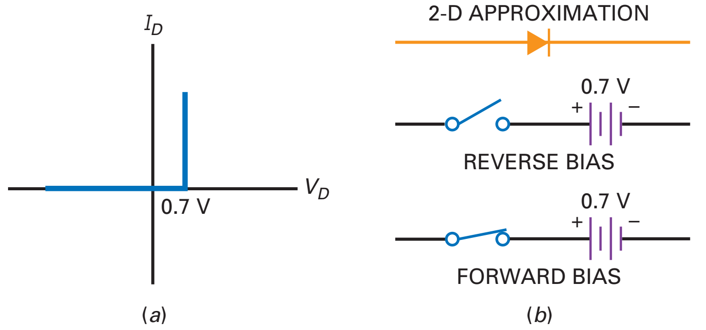
The ideal approximation is all right in most troubleshooting situations. But we are not always troubleshooting. Sometimes, we want a more accurate value for load current and load voltage. This is where the *second approximation* comes in.

Figure 3-7*a* shows the graph of current versus voltage for the second approximation. The graph says that no current exists until 0.7 V appears across the diode. At this point, the diode turns on. Thereafter, only 0.7 V can appear across the diode, no matter what the current.

Figure 3-7*b* shows the equivalent circuit for the second approximation of a silicon diode. We think of the diode as a switch in series with a barrier potential of 0.7 V. If the Thevenin voltage facing the diode is greater than 0.7 V, the switch will close. When conducting, then the diode voltage is 0.7 V for any forward current.

On the other hand, if the Thevenin voltage is less than 0.7 V, the switch will open. In this case, there is no current through the diode.

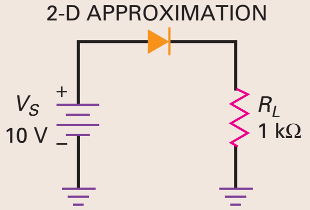
Figure 3-7 (*a*) Diode curve for second approximation; (*b*) equivalent circuit for second approximation.



Example 3-5

Use the second approximation to calculate the load voltage, load current, and diode power in Fig. 3-8.

Figure 3-8



SOLUTION Since the diode is forward biased, it is equivalent to a battery of 0.7 V. This means that the load voltage equals the source voltage minus the diode drop:

$$V_L = 10\ \text{V} - 0.7\ \text{V} = 9.3\ \text{V}$$

With Ohm's law, the load current is:

$$I_L = \frac{9.3\ \text{V}}{1\ \text{k}\Omega} = 9.3\ \text{mA}$$

The diode power is

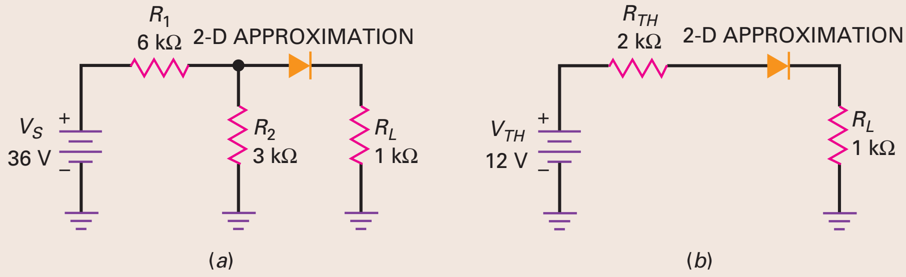
$$P_D = (0.7\ \text{V})(9.3\ \text{mA}) = 6.51\ \text{mW}$$

PRACTICE PROBLEM 3-5 Using Fig. 3-8, change the source voltage to 5 V and calculate the new load voltage, current, and diode power.

Example 3-6

Calculate the load voltage, load current, and diode power in Fig. 3-9*a* using the second approximation.

Figure 3-9 (*a*) Original circuit; (*b*) simplified with Thevenin's theorem.



SOLUTION Again, we will Thevenize the circuit to the left of the diode. As before, the Thevenin voltage is 12 V and the Thevenin resistance is 2 kΩ. Figure 3-9*b* shows the simplified circuit.

Since the diode voltage is 0.7 V, the load current is:

$$I_L = \frac{12\ \text{V} - 0.7\ \text{V}}{3\ \text{k}\Omega} = 3.77\ \text{mA}$$

The load voltage is:

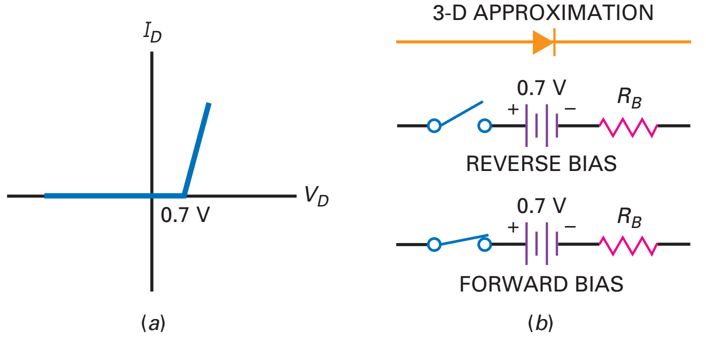
$$V_L = (3.77\ \text{mA})(1\ \text{k}\Omega) = 3.77\ \text{V}$$

and the diode power is:

$$P_D = (0.7\ \text{V})(3.77\ \text{mA}) = 2.64\ \text{mW}$$

PRACTICE PROBLEM 3-6 Repeat Example 3-6 using 18 V as the voltage source value.

Figure 3-10 (*a*) Diode curve for third approximation; (*b*) equivalent circuit for third approximation.



3-4 The Third Approximation

In the *third approximation* of a diode, we include the bulk resistance R_B. Figure 3-10*a* shows the effect that R_B has on the diode curve. After the silicon diode turns on, the voltage increases linearly with an increase in current. The greater the current, the larger the diode voltage because of the voltage drop across the bulk resistance.

The equivalent circuit for the third approximation is a switch in series with a barrier potential of 0.7 V and a resistance of R_B (see Fig. 3-10*b*). When the diode voltage is larger than 0.7 V, the diode conducts. During conduction, the total voltage across the diode is:

$$V_D = 0.7\text{ V} + I_D R_B \tag{3-5}$$

Often, the bulk resistance is less than 1 Ω, and we can safely ignore it in our calculations. A useful guideline for ignoring bulk resistance is this definition:

$$\textbf{Ignore bulk: } R_B < 0.01 R_{TH} \tag{3-6}$$

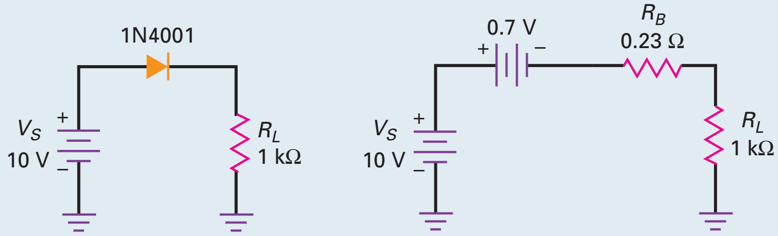
This says to ignore the bulk resistance when it is less than 1/100 of the Thevenin resistance facing the diode. When this condition is satisfied, the error is less than 1 percent. The third approximation is rarely used by technicians because circuit designers usually satisfy Eq. (3-6).

Application Example 3-7

The 1N4001 of Fig. 3-11*a* has a bulk resistance of 0.23 Ω. What is the load voltage, load current, and diode power?

SOLUTION Replacing the diode with its third approximation, we get Fig. 3-11*b*. The bulk resistance is small enough to ignore because it is less than 1/100 of the load resistance. In this case, we can use the second approximation to solve the problem. We already did this in Example 3-6, where we found a load voltage, load current, and diode power of 9.3 V, 9.3 mA, and 6.51 mW.

Figure 3-11



(*a*) (*b*)

Application Example 3-8

Repeat the preceding example for a load resistance of 10 Ω.

SOLUTION Figure 3-12*a* shows the equivalent circuit. The total resistance is:

$$R_T = 0.23\ \Omega + 10\ \Omega = 10.23\ \Omega$$

The total voltage across R_T is:

$$V_T = 10\text{ V} - 0.7\text{ V} = 9.3\text{ V}$$

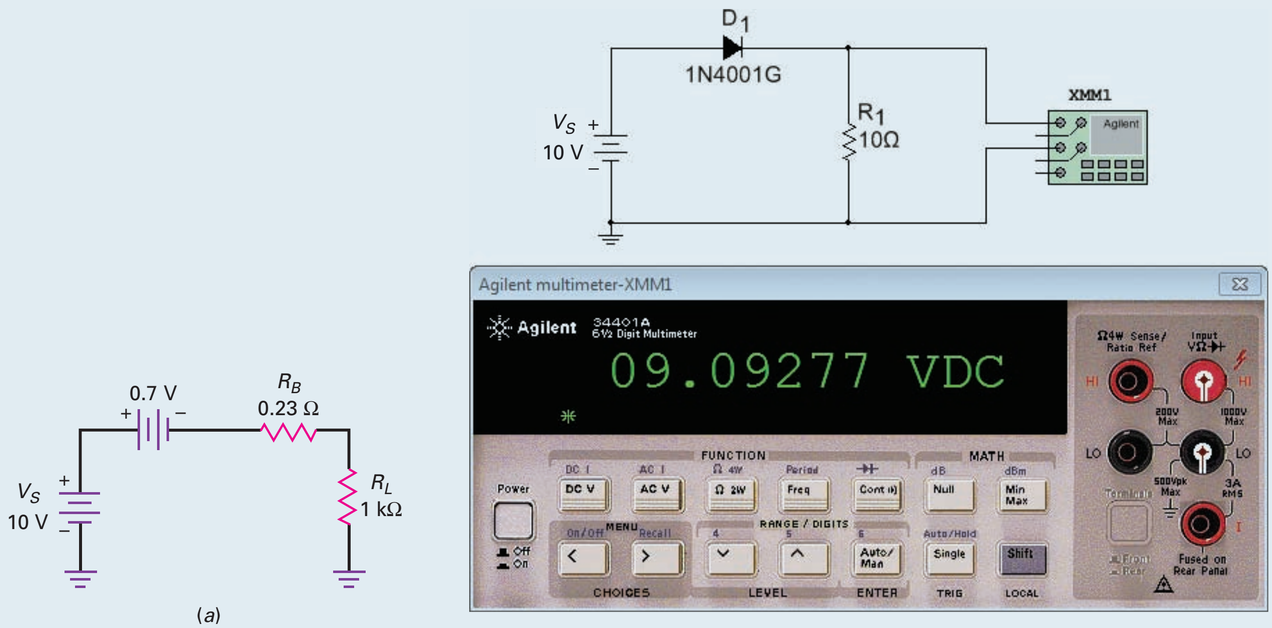
Therefore, the load current is:

$$I_L = \frac{9.3\text{ V}}{10.23\ \Omega} = 0.909\text{ A}$$

The load voltage is:

$$V_L = (0.909\text{ A})(10\ \Omega) = 9.09\text{ V}$$

Figure 3-12



(*a*) (*b*)

To calculate the diode power, we need to know the diode voltage. We can get this in either of two ways. We can subtract the load voltage from the source voltage:

$$V_D = 10\text{ V} - 9.09\text{ V} = 0.91\text{ V}$$

or we can use Eq. (3-5):

$$V_D = 0.7\text{ V} + (0.909\text{ A})(0.23\ \Omega) = 0.909\text{ V}$$

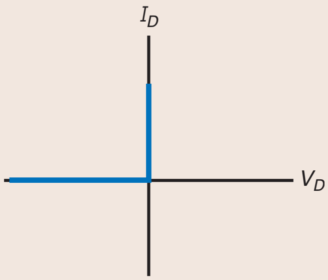
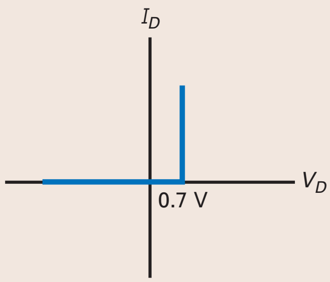
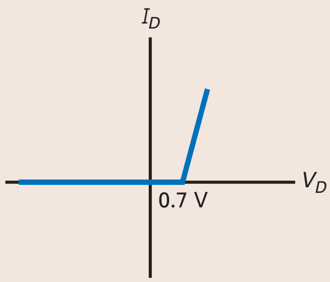
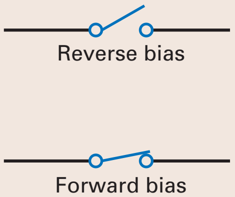
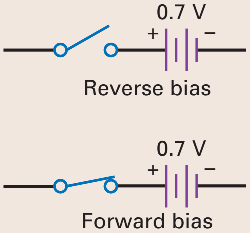
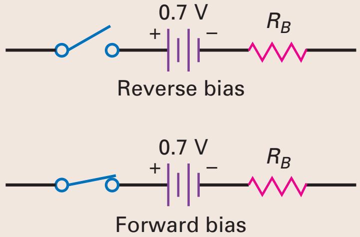
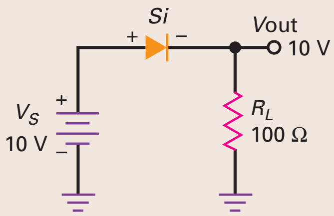
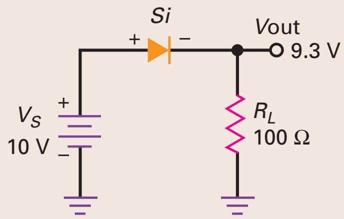
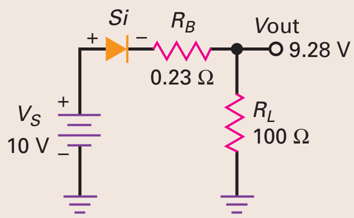
The slight difference in the last two answers is caused by rounding. The diode power is:

$$P_D = (0.909\text{ V})(0.909\text{ A}) = 0.826\text{ W}$$

Two more points. First, the 1N4001 has a maximum forward current of 1 A and a power rating of 1 W, so the diode is being pushed to its limits with a load resistance of 10 Ω. Second, the load voltage calculated with the third approximation is 9.09 V, which is in agreement with the Multisim load voltage (see Fig. 3-12*b*).

Summary Table 3-1 illustrates the differences between the three diode approximations.

Summary Table 3-1 Diode Approximations

	First or ideal	Second or practical	Third
When used	Troubleshooting or quick analysis	Analysis at technician level	High-level or engineering-level analysis
Diode curve			
Equivalent circuit			
Circuit example			

PRACTICE PROBLEM 3-8 Repeat Application Example 3-8 using 5 V as the voltage source value.

3-5 Troubleshooting

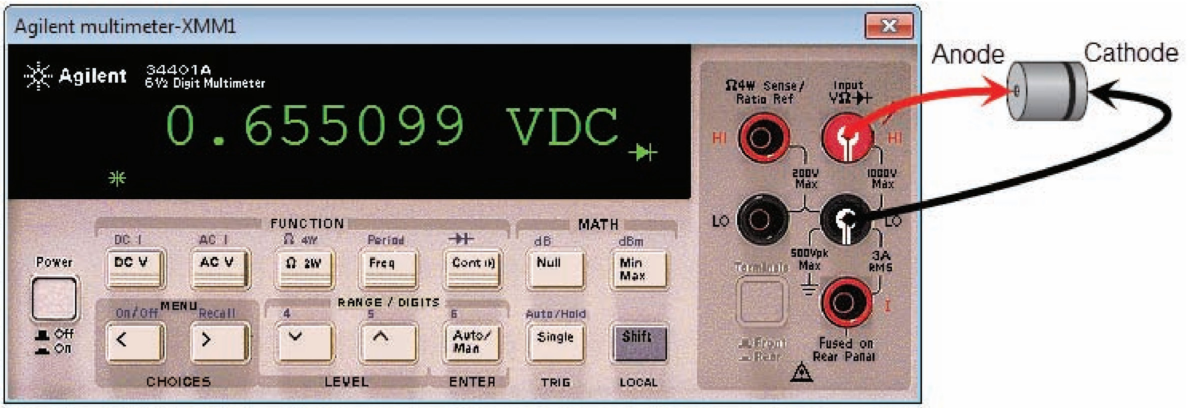
You can quickly check the condition of a diode with an ohmmeter on a medium-to-high resistance range. Measure the dc resistance of the diode in either direction, and then reverse the leads and measure the dc resistance again. The forward current will depend on which ohmmeter range is used, which means that you get different readings on different ranges.

The main thing to look for, however, is a high ratio of reverse to forward resistance. For typical silicon diodes used in electronics work, the ratio should be higher than 1000:1. Remember to use a high enough resistance range to avoid the possibility of diode damage. Normally, the R $\times$ 100 or R $\times$ 1K ranges will provide proper safe measurements.

Using an ohmmeter to check diodes is an example of go/no-go testing. You're really not interested in the exact dc resistance of the diode; all you want to know is whether the diode has a low resistance in the forward direction and a high resistance in the reverse direction. Diode troubles are indicated for any of the following: extremely low resistance in both directions (diode shorted); high resistance in both directions (diode open); somewhat low resistance in the reverse direction (called a *leaky diode*).

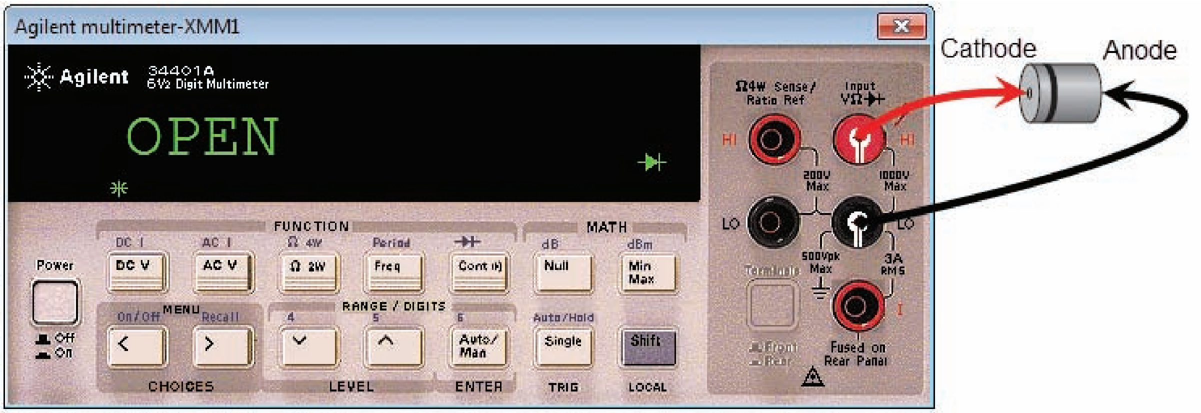
When set to the ohms or resistance function, most digital multimeters (DMMs) do not have the required voltage and current output capability to properly test *pn*-junction diodes. Most DMMs do, however, have a special diode test range. When the meter is set to this range, it supplies a constant current of approximately 1 mA to whatever device is connected to its leads. When forward biased, the DMM will display the *pn* junction's forward voltage V_F shown in Fig. 3-13*a*. This forward voltage will generally be between 0.5 V and 0.7 V for normal silicon *pn*-junction diodes. When the diode is reverse biased by the test leads, the meter will give an overrange indication such as "OL" or "1" on the display as shown in Fig. 3-13*b*. A shorted diode would display a voltage of less than 0.5 V in both directions. An open diode would be indicated by an overrange display in both directions. A leaky diode would display a voltage less than 2.0 V in both directions.

Figure 3-13 (*a*) DMM diode forward test.



(*a*)

Figure 3-13 (*b*) DMM diode reverse test.



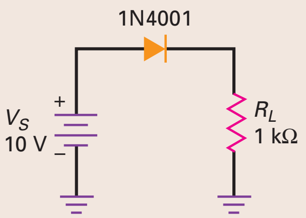
(*b*)

Example 3-9

Figure 3-14 shows the diode circuit analyzed earlier. Suppose something causes the diode to burn out. What kind of symptoms will you get?

SOLUTION When a diode burns out, it becomes an open circuit. In this case, the current drops to zero. Therefore, if you measure the load voltage, the voltmeter will indicate zero.

Figure 3-14 Troubleshooting a circuit.



Example 3-10

Suppose the circuit in Fig. 3-14 is not working. If the load is not shorted, what is the trouble?

SOLUTION Many troubles are possible. First, the diode could be open. Second, the supply voltage could be zero. Third, one of the connecting wires could be open.

How do you find the trouble? Measure the voltages to isolate the defective component. Then disconnect any suspected component and test its resistance. For instance, you could measure the source voltage first and the load voltage second. If there is source voltage but no load voltage, the diode may be open. An ohmmeter or DMM test will tell. If the diode passes the ohmmeter or DMM test, check the connections because there's nothing else to account for having source voltage but no load voltage.

If there is no source voltage, the power supply is defective or a connection between the supply and the diode is open. Power-supply troubles are common. Often, when electronics equipment is not working, the trouble is in the power supply. This is why most troubleshooters start by measuring the voltages out of the power supply.

3-6 Reading a Data Sheet

GOOD TO KNOW

Internet search engines, such as Google, can quickly help locate semiconductor specifications.

A data sheet, or specification sheet, lists important parameters and operating characteristics for semiconductor devices. Also, essential information such as case styles, pinouts, testing procedures, and typical applications can be obtained from a component's data sheet. Semiconductor manufacturers generally provide this information in data books or on the manufacturer's website. This information can also be found on the Internet by companies that specialize in cross-referencing or component substitution.

Much of the information on a manufacturer's data sheet is obscure and of use only to circuit designers. For this reason, we will discuss only those entries on the data sheet that describe quantities in this book.

Reverse Breakdown Voltage

Let us start with the data sheet for a 1N4001, a rectifier diode used in power supplies (circuits that convert ac voltage to dc voltage). Figure 3-15 shows a data sheet for the 1N4001 to 1N4007 series of diodes: seven diodes that have the same forward characteristics but differ in their reverse characteristics. We are interested in the 1N4001 member of this family. The first entry under "Absolute Maximum Ratings" is this:

	Symbol	1N4001
Peak Repetitive Reverse Voltage	V_{RRM}	50 V

The breakdown voltage for this diode is 50 V. This breakdown occurs because the diode goes into avalanche when a huge number of carriers suddenly appears in the depletion layer. With a rectifier diode like the 1N4001, breakdown is usually destructive.

With the 1N4001, a reverse voltage of 50 V represents a destructive level that a designer avoids under all operating conditions. This is why a designer includes a *safety factor*. There is no absolute rule on how large to make the safety factor because it depends on too many design factors. A conservative design would use a safety factor of 2, which means never allowing a reverse voltage of more than 25 V across the 1N4001. A less conservative design might allow as much as 40 V across the 1N4001.

On other data sheets, reverse breakdown voltage may be designated *PIV*, *PRV*, or *BV*.

Maximum Forward Current

Another entry of interest is average rectified forward current, which looks like this on the data sheet:

	Symbol	Value
Average Rectified Forward Current @ $T_A = 75°C$	$I_{F(AV)}$	1 A

This entry tells us that the 1N4001 can handle up to 1 A in the forward direction when used as a rectifier. You will learn more about average rectified forward current in the next chapter. For now, all you need to know is that 1 A is the level of

Figure 3-15 Data sheet for 1N4001–1N4007 diodes. (Copyright Fairchild Semiconductor Corporation. Used by permission.)

FAIRCHILD
SEMICONDUCTOR®

May 2009

1N4001 - 1N4007
General Purpose Rectifiers

Features

- Low forward voltage drop.
- High surge current capability.

DO-41
COLOR BAND DENOTES CATHODE

Absolute Maximum Ratings * T_A = 25°C unless otherwise noted

Symbol	Parameter	Value							Units
		4001	4002	4003	4004	4005	4006	4007	
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
$I_{F(AV)}$	Average Rectified Forward Current .375 " lead length @ T_A = 75°C	1.0							A
I_{FSM}	Non-Repetitive Peak Forward Surge Current 8.3ms Single Half-Sine-Wave	30							A
I^2t	Rating for Fusing (t<8.3ms)	3.7							A^2sec
T_{STG}	Storage Temperature Range	-55 to +175							°C
T_J	Operating Junction Temperature	-55 to +175							°C

* These ratings are limiting values above which the serviceability of any semiconductor device may by impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	3.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W

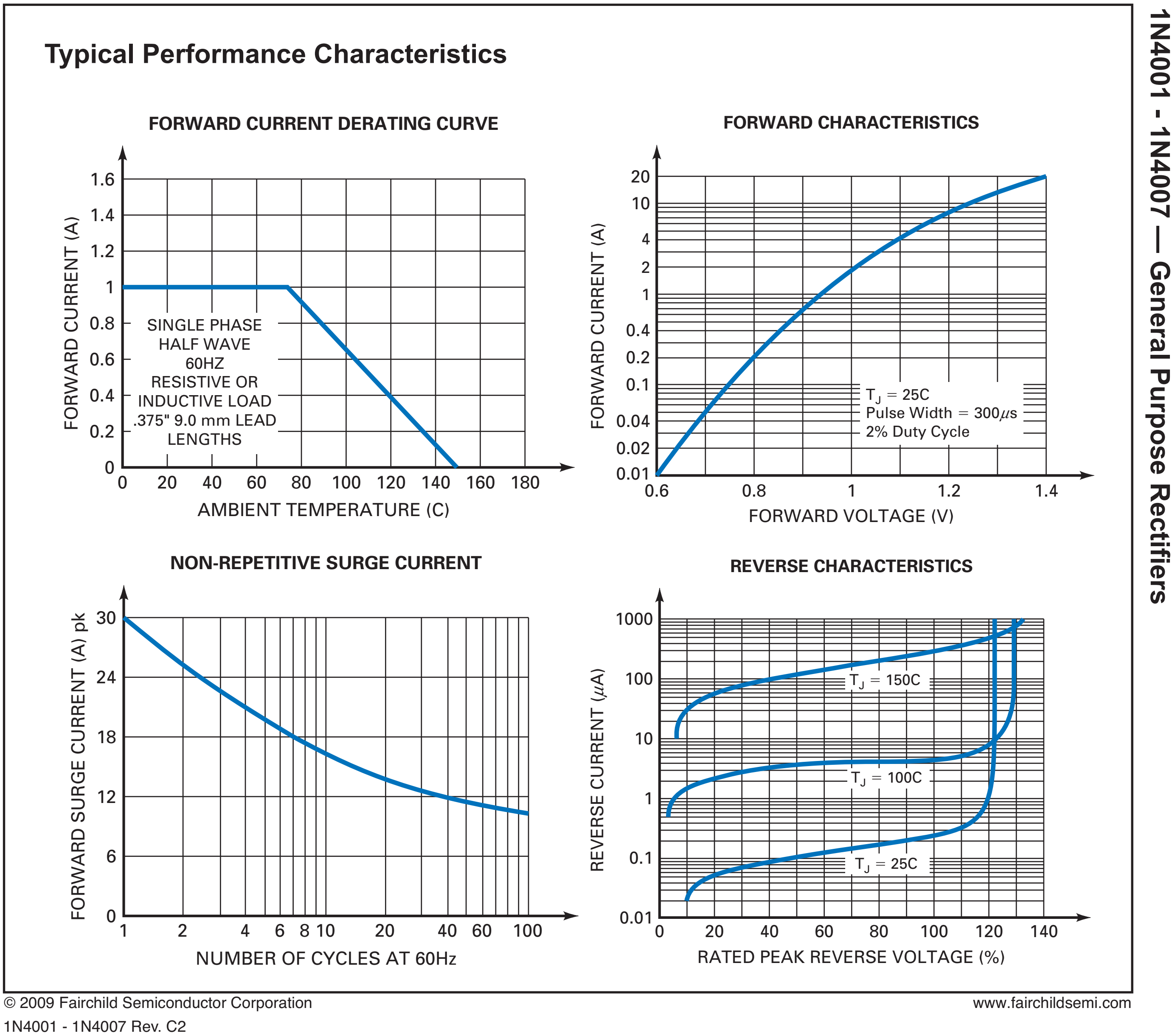
Electrical Characteristics T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_F	Forward Voltage @ 1.0A	1.1	V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30	µA
I_R	Reverse Current @ Rated V_R T_A = 25°C T_A = 100°C	5.0 50	µA µA
C_T	Total Capacitance V_R = 4.0V, f = 1.0MHz	15	pF

© 2009 Fairchild Semiconductor Corporation

(*a*)

Figure 3-15 (continued)



(*b*)

forward current when the diode burns out because of excessive power dissipation. On other data sheets, the average current may be designated as I_o.

Again, a designer looks upon 1 A as the absolute maximum rating of the 1N4001, a level of forward current that should not even be approached. This is why a safety factor would be included—possibly a factor of 2. In other words, a reliable design would ensure that the forward current is less than 0.5 A under all operating conditions. Failure studies of devices show that the lifetime of a device decreases the closer you get to the maximum rating. This is why some designers use a safety factor of as much as 10:1. A really conservative design would keep the maximum forward current of the 1N4001 at 0.1 A or less.

Forward Voltage Drop

Under "Electrical Characteristics" in Fig. 3-15, the first entry shown gives you the following data:

Characteristic and Conditions	Symbol	Maximum Value
Forward Voltage Drop (i_F) = 1.0 A, T_A = 25°C	V_F	1.1 V

As shown in Fig. 3-15 on the chart titled "Forward Characteristics," the typical 1N4001 has a forward voltage drop of 0.93 V when the current is 1 A and the junction temperature is 25°C. If you test thousands of 1N4001s, you will find that a few will have as much as 1.1 V across them when the current is 1 A.

Maximum Reverse Current

Another entry on the data sheet that is worth discussing is this one:

Characteristic and Conditions	Symbol	Maximum Value
Reverse Current	I_R	
T_A = 25°C		10 μA
T_A = 100°C		50 μA

This is the reverse current at the maximum reverse dc rated voltage (50 V for a 1N4001). At 25°C, the 1N4001 has a maximum reverse current of 10 μA. But notice how it increases to 50 μA at 100°C. Remember that this reverse current includes thermally produced saturation current and surface-leakage current. You can see from these numbers that temperature is important. A design that requires a reverse current of less than 10 μA will work fine at 25°C with a 1N4001, but will fail in mass production if the junction temperature reaches 100°C.

3-7 How to Calculate Bulk Resistance

When you are trying to analyze a diode circuit accurately, you will need to know the bulk resistance of the diode. Manufacturers' data sheets do not usually list the bulk resistance separately, but they do give enough information to allow you to calculate it. Here is the derivation for bulk resistance:

$$\boldsymbol{R_B = \frac{V_2 - V_1}{I_2 - I_1}} \tag{3-7}$$

where V_1 and I_1 are the voltage and current at some point at or above the knee voltage; V_2 and I_2 are the voltage and current at some higher point on the diode curve.

For instance, the data sheet of a 1N4001 gives a forward voltage of 0.93 V for a current of 1 A. Since this is a silicon diode, it has a knee voltage of approximately 0.7 V and a current of approximately zero. Therefore, the values to use are $V_2 = 0.93$ V, $I_2 = 1$ A, $V_1 = 0.7$ V, and $I_1 = 0$. Substituting these values into an equation, we get a bulk resistance of:

$$R_B = \frac{V_2 - V_1}{I_2 - I_1} = \frac{0.93\text{ V} - 0.7\text{ V}}{1\text{ A} - 0\text{ A}} = \frac{0.23\text{ V}}{1\text{ A}} = 0.23\ \Omega$$

Incidentally, the diode curve is a graph of current versus voltage. The bulk resistance equals the inverse of the slope above the knee. The greater the slope of the diode curve, the smaller the bulk resistance. In other words, the more vertical the diode curve is above the knee, the lower the bulk resistance.

3-8 DC Resistance of a Diode

If you take the ratio of total diode voltage to total diode current, you get the *dc resistance* of the diode. In the forward direction, this dc resistance is symbolized by R_F; in the reverse direction, it is designated R_R.

Forward Resistance

Because the diode is a nonlinear device, its dc resistance varies with the current through it. For example, here are some pairs of forward current and voltage for a 1N914: 10 mA at 0.65 V, 30 mA at 0.75 V, and 50 mA at 0.85 V. At the first point, the dc resistance is:

$$R_F = \frac{0.65 \text{ V}}{10 \text{ mA}} = 65 \ \Omega$$

At the second point:

$$R_F = \frac{0.75 \text{ V}}{30 \text{ mA}} = 25 \ \Omega$$

And at the third point:

$$R_F = \frac{0.85 \text{ mV}}{50 \text{ mA}} = 17 \ \Omega$$

Notice how the dc resistance decreases as the current increases. In any case, the forward resistance is low compared to the reverse resistance.

Reverse Resistance

Similarly, here are two sets of reverse current and voltage for a 1N914: 25 nA at 20 V; 5 μA at 75 V. At the first point, the dc resistance is:

$$R_R = \frac{20 \text{ V}}{25 \text{ nA}} = 800 \text{ M}\Omega$$

At the second point:

$$R_R = \frac{75 \text{ V}}{5 \ \mu\text{A}} = 15 \text{ M}\Omega$$

Notice how the dc resistance decreases as we approach the breakdown voltage (75 V).

DC Resistance versus Bulk Resistance

The dc resistance of a diode is different from the bulk resistance. The dc resistance of a diode equals the bulk resistance *plus* the effect of the barrier potential. In other words, the dc resistance of a diode is its total resistance, whereas the bulk resistance is the resistance of only the *p* and *n* regions. For this reason, the dc resistance of a diode is always greater than the bulk resistance.

3-9 Load Lines

This section is about the **load line,** a tool used to find the exact value of diode current and voltage. Load lines are useful with transistors, so a detailed explanation will be given later in the transistor discussions.

Equation for the Load Line

How can we find the exact diode current and voltage in Fig. 3-16*a*? The current through the resistor is:

$$I_D = \frac{V_S - V_D}{R_s} \tag{3-8}$$

Because of the series circuit, this current is the same through the diode.

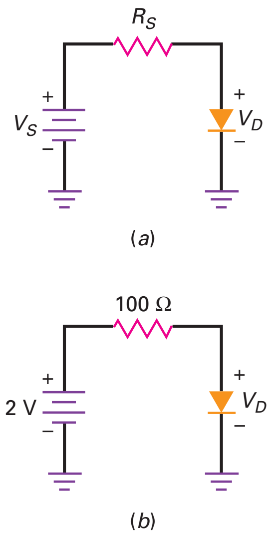


Figure 3-16 Load-line analysis.

An Example

If the source voltage is 2 V and the resistance is 100 Ω as shown in Fig. 3-16*b*, then Eq. (3-8) becomes:

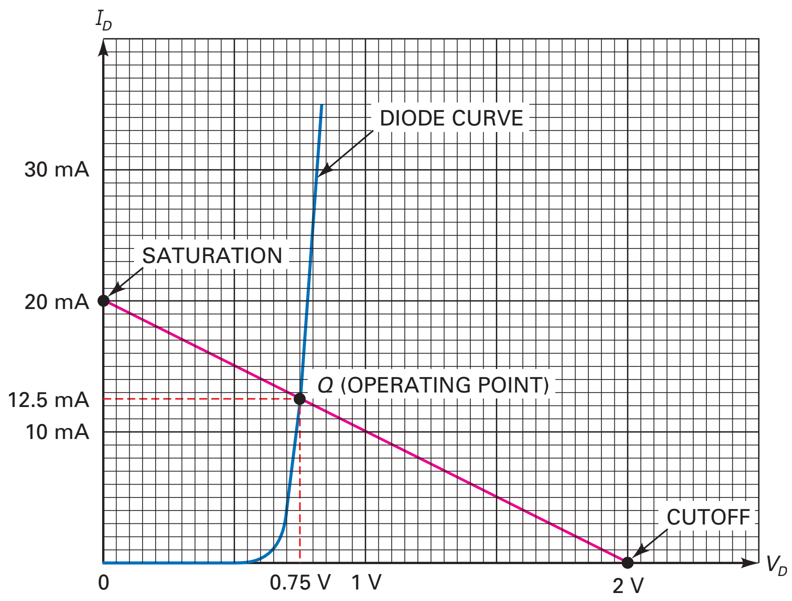
$$I_D = \frac{2 - V_D}{100} \tag{3-9}$$

Equation (3-9) is a linear relationship between current and voltage. If we plot this equation, we will get a straight line. For instance, let V_D equal zero. Then:

$$I_D = \frac{2\text{ V} - 0\text{ V}}{100\ \Omega} = 20\text{ mA}$$

Plotting this point ($I_D = 20$ mA, $V_D = 0$) gives the point on the vertical axis of Fig. 3-17. This point is called *saturation* because it represents maximum current with 2 V across 100 Ω.

Figure 3-17 *Q* point is the intersection of the diode curve and the load line.



Here's how to get another point. Let V_D equal 2 V. Then Eq. (3-9) gives:

$$I_D = \frac{2\text{ V} - 2\text{ V}}{100\ \Omega} = 0$$

When we plot this point ($I_D = 0$, $V_D = 2$ V), we get the point shown on the horizontal axis (Fig. 3-17). This point is called *cutoff* because it represents minimum current.

By selecting other voltages, we can calculate and plot additional points. Because Eq. (3-9) is linear, all points will lie on the straight line shown in Fig. 3-17. The straight line is called the *load line.*

The *Q* Point

Figure 3-17 shows the load line and a diode curve. The point of intersection, known as the *Q* point, represents a simultaneous solution between the diode curve and the load line. In other words, the *Q* point is the only point on the graph that works for both the diode and the circuit. By reading the coordinates of the *Q* point, we get a current of 12.5 mA and a diode voltage of 0.75 V.

Incidentally, the *Q* point has no relationship to the figure of merit of a coil. In the present discussion, *Q* is an abbreviation for *quiescent,* which means "at rest." The quiescent or *Q* point of semiconductor circuits is discussed in later chapters.

3-10 Surface-Mount Diodes

Surface-mount (SM) diodes can be found anywhere there is a need for diode applications. SM diodes are small, efficient, and relatively easy to test, remove, and replace on the circuit board. Although there are a number of SM package styles, two basic styles dominate the industry: SM (surface mount) and SOT (small outline transistor).

The SM package has two L-bend leads and a colored band on one end of the body to indicate the cathode lead. Figure 3-18 shows a typical set of dimensions. The length and width of the SM package are related to the current rating of the device. The larger the surface area, the higher the current rating. So an SM diode rated at 1 A might have a surface area given by 0.181 by 0.115 in. The 3 A version, on the other hand, might measure 0.260 by 0.236 in. The thickness tends to remain at about 0.103 in for all current ratings.

Figure 3-18 The two-terminal SM-style package used for SM diodes.

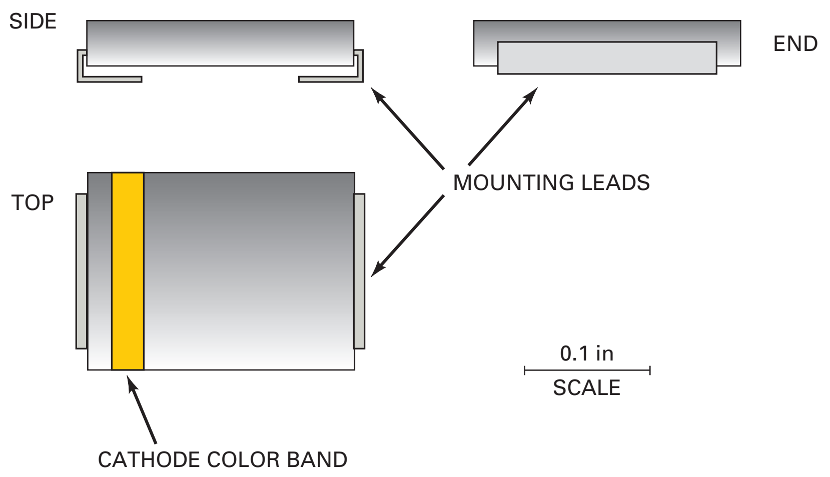
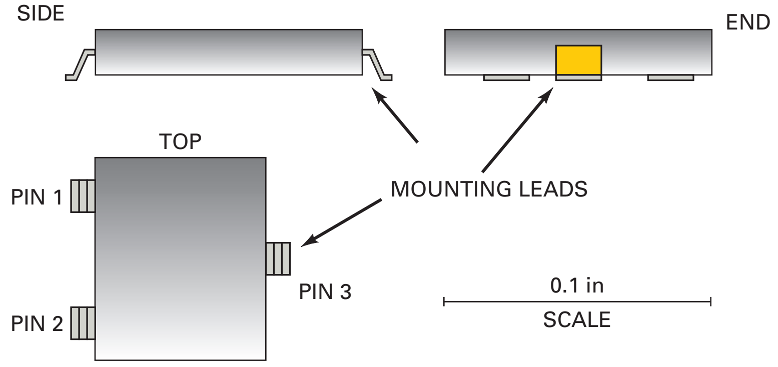


Figure 3-19 The SOT-23 is a three-terminal transistor package commonly used for SM diodes.



Increasing the surface area of an SM-style diode increases its ability to dissipate heat. Also, the corresponding increase in the width of the mounting terminals increases the thermal conductance to a virtual heat sink made up of the solder joints, mounting lands, and the circuit board itself.

SOT-23 packages have three gull-wing terminals (see Fig. 3-19). The terminals are numbered counterclockwise from the top, pin 3 being alone on one side. However, there are no standard markings indicating which two terminals are used for the cathode and the anode. To determine the internal connections of the diode, you can look for clues printed on the circuit board, check the schematic diagram, or consult the diode manufacturer's data book. Some SOT-style packages include two diodes, which have a common-anode or common-cathode connection at one of the terminals.

Diodes in SOT-23 packages are small, no dimension being greater than 0.1 in. Their small size makes it difficult to dissipate larger amounts of heat, so the diodes are generally rated at less than 1 A. The small size also makes it impractical to label them with identification codes. As with many of the tiny SM devices, you have to determine the pin configuration from other clues on the circuit board and schematic diagram.

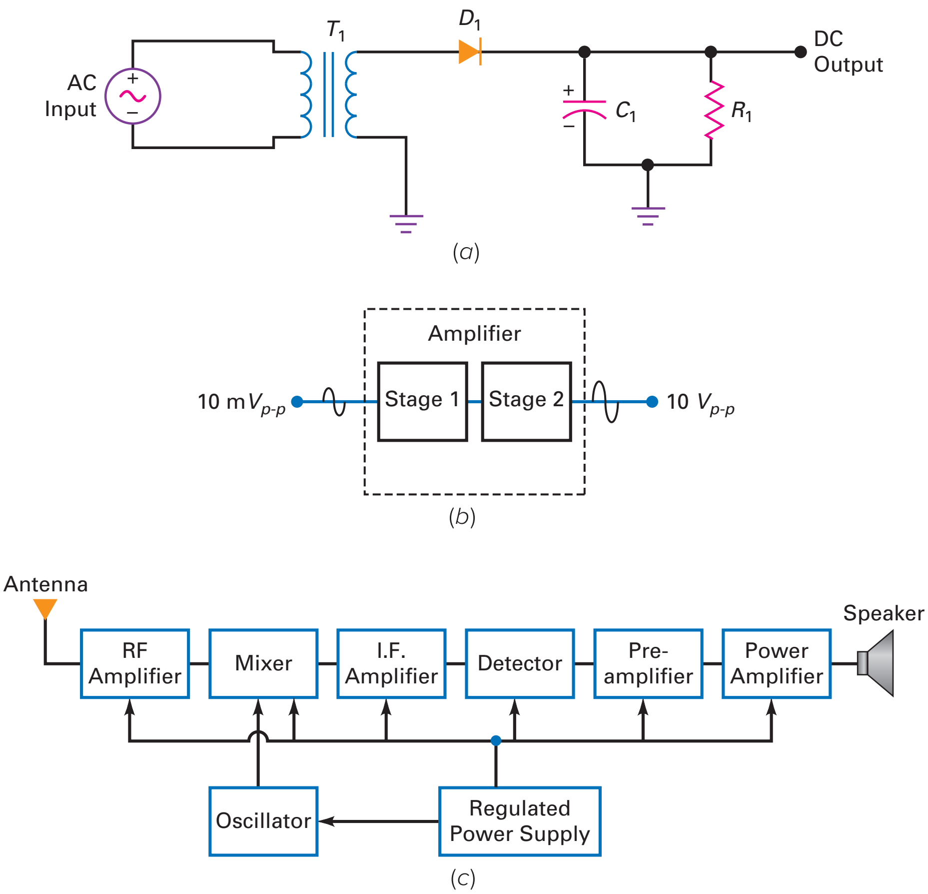
3-11 Introduction to Electronic Systems

In your study of *Electronic Principles,* you will be introduced to a variety of electronic semiconductor devices. Each of these devices will have unique properties and characteristics. Your knowledge of how these individual components function is very important. But this is just the beginning.

These electronic devices normally do not function on their own. Instead, with the addition of other electronic components, such as resistors, capacitors, inductors, and other semiconductor devices, they are interconnected to form electronic circuits. These electronic circuits are often categorized into subsets, such as analog circuits and digital circuits, or application specific circuits as amplifiers, converters, rectifiers, and so on. While analog circuits operate with infinitely varying quantities, often referred to as linear electronics, digital circuits generally operate with signal levels found in two distinct states representing logical or numeric values. A basic diode rectifier circuit, using a transformer, diode, capacitor, and resistor, is shown in Fig. 3-20*a*.

What happens when different types of circuits are connected together? By combining a variety of circuits, functional blocks can be formed. These blocks, which can be made up of multiple stages, are designed to take a specific type of

Figure 3-20 (*a*) Basic diode rectifier circuit; (*b*) amplifier functional block; (*c*) communication receiver block diagram.



input signal and produce the desired output. As an example, Fig. 3-20*b* is an amplifier, with two stages, used to increase signal levels from an input of 10 mVp-p to an output of 10 Vp-p.

Can electronic functional blocks be interconnected? Absolutely! This is when the study of electronics becomes so dynamic and diverse. These interconnected electronic function blocks are essentially grouped together to create **electronic systems.** Electronic systems can be found in a variety of areas including automation and industrial control, communications, computer information, security systems and more. Fig. 3-20*c* is a block diagram of a basic communications receiver system broken down into functional blocks. This type of diagram is very useful when troubleshooting systems.

In summary, semiconductor components are combined with other components to form circuits. Circuits can be combined to become functional blocks. Functional blocks can be interconnected to form electronic systems. To go one step further, electronic systems are often connected to form complex systems.

To help understand how these concepts all work together, this chapter introduces a Digital/Analog Trainer System. This trainer is used for building, testing, and prototyping analog and digital circuits. Many of the electronic devices found in following chapters are used in this trainer. Some chapters in this textbook will have end-of-chapter questions referring to this trainer system. This will give you experience seeing how individual electronic components work together and how circuits function together.

The schematic diagram for this trainer system can be found on the Instructor Resources section of *Connect for Electronic Principles*.