2.2 LOAD-LINE ANALYSIS

The applied load will normally have an important impact on the point or region of operation of a device. If the analysis is performed in a graphical manner, a line can be drawn on the characteristics of the device that represents the applied load. The intersection of the load line with the characteristics will determine the point of operation of the system. Such an analysis is, for obvious reasons, called *load-line analysis*. Although the majority of the diode networks analyzed in this chapter do not employ the load-line approach, the technique is one used quite frequently in subsequent chapters, and this introduction offers the simplest application of the method. It also permits a validation of the approximate technique described throughout the remainder of this chapter.

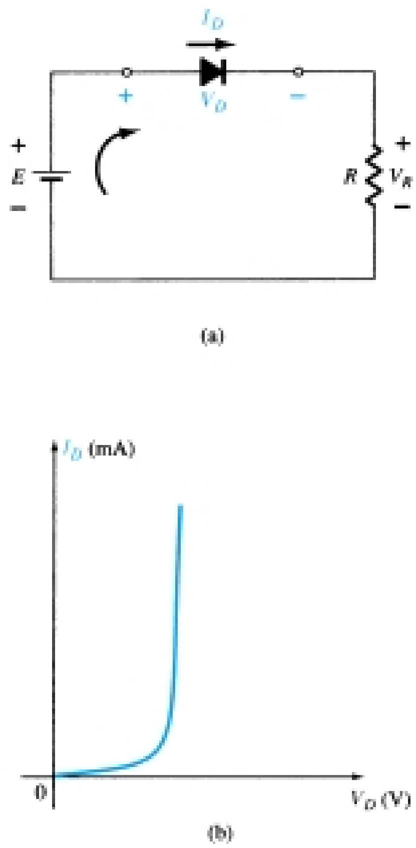


Figure 2.1 Series diode configuration: (a) circuit; (b) characteristics.

Consider the network of Fig. 2.1a employing a diode having the characteristics of Fig. 2.1b. Note in Fig. 2.1a that the "pressure" established by the battery is to establish a current through the series circuit in the clockwise direction. The fact that this current and the defined direction of conduction of the diode are a "match" reveals that the diode is in the "on" state and conduction has been established. The resulting polarity across the diode will be as shown and the first quadrant (V_D and I_D positive) of Fig. 2.1b will be the region of interest—the forward-bias region.

Applying Kirchhoff's voltage law to the series circuit of Fig. 2.1a will result in

$$E - V_D - V_R = 0$$

or

$$\boxed{E = V_D + I_D R} \tag{2.1}$$

The two variables of Eq. (2.1) (V_D and I_D) are the same as the diode axis variables of Fig. 2.1b. This similarity permits a plotting of Eq. (2.1) on the same characteristics of Fig. 2.1b.

The intersections of the load line on the characteristics can easily be determined if one simply employs the fact that anywhere on the horizontal axis $I_D = 0$ A and anywhere on the vertical axis $V_D = 0$ V.

If we *set* $V_D = 0$ V in Eq. (2.1) and solve for I_D, we have the magnitude of I_D *on* the vertical axis. Therefore, with $V_D = 0$ V, Eq. (2.1) becomes

$$E = V_D + I_D R$$

$$= 0 \text{ V} + I_D R$$

and

$$\boxed{I_D = \frac{E}{R}\bigg|_{V_D = 0 \text{ V}}} \tag{2.2}$$

as shown in Fig. 2.2. If we *set* $I_D = 0$ A in Eq. (2.1) and solve for V_D, we have the magnitude of V_D *on* the horizontal axis. Therefore, with $I_D = 0$ A, Eq. (2.1) becomes

$$E = V_D + I_D R$$

$$= V_D + (0 \text{ A})R$$

and

$$\boxed{V_D = E|_{I_D = 0 \text{ A}}} \tag{2.3}$$

as shown in Fig. 2.2. A straight line drawn between the two points will define the load line as depicted in Fig. 2.2. Change the level of R (the load) and the intersection on the vertical axis will change. The result will be a change in the slope of the load line and a different point of intersection between the load line and the device characteristics.

We now have a load line defined by the network and a characteristic curve defined by the device. The point of intersection between the two is the point of opera-

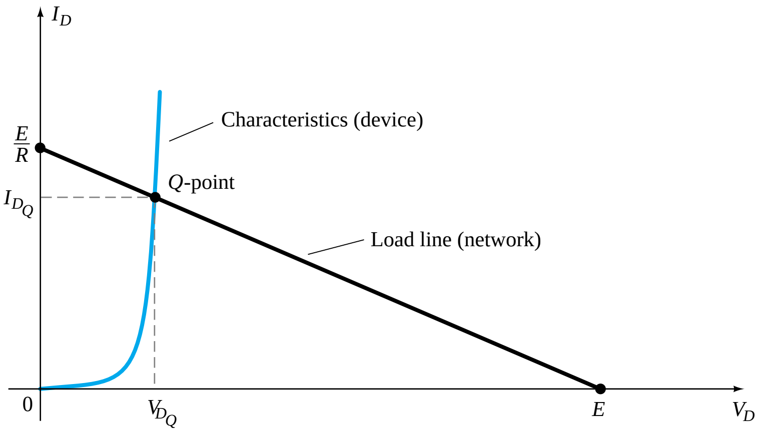


Figure 2.2 Drawing the load line and finding the point of operation.

tion for this circuit. By simply drawing a line down to the horizontal axis the diode voltage V_{D_Q} can be determined, whereas a horizontal line from the point of intersection to the vertical axis will provide the level of I_{D_Q}. The current I_D is actually the current through the entire series configuration of Fig. 2.1a. The point of operation is usually called the *quiescent point* (abbreviated "*Q*-pt.") to reflect its "still, unmoving" qualities as defined by a dc network.

The solution obtained at the intersection of the two curves is the same that would be obtained by a simultaneous mathematical solution of Eqs. (2.1) and (1.4) $[I_D = I_s(e^{kV_D/T_K} - 1)]$. Since the curve for a diode has nonlinear characteristics the mathematics involved would require the use of nonlinear techniques that are beyond the needs and scope of this book. The load-line analysis described above provides a solution with a minimum of effort and a "pictorial" description of why the levels of solution for V_{D_Q} and I_{D_Q} were obtained. The next two examples will demonstrate the techniques introduced above and reveal the relative ease with which the load line can be drawn using Eqs. (2.2) and (2.3).

EXAMPLE 2.1

For the series diode configuration of Fig. 2.3a employing the diode characteristics of Fig. 2.3b determine:

(a) V_{D_Q} and I_{D_Q}.
(b) V_R.

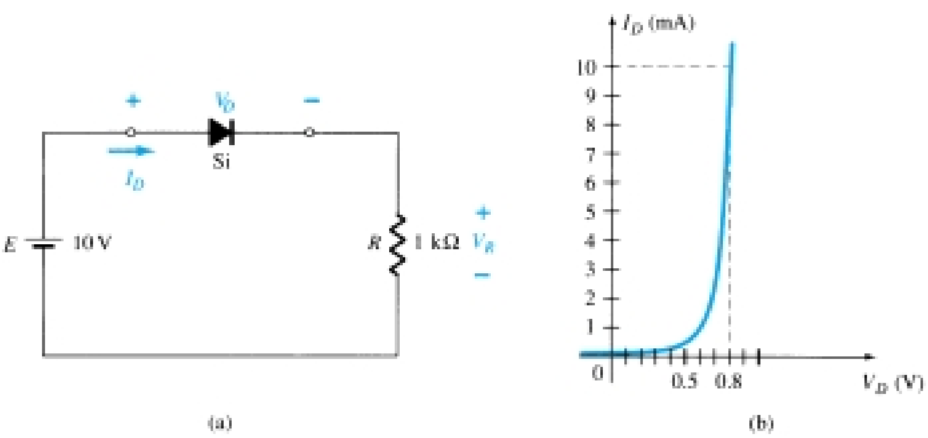


Figure 2.3 (a) Circuit; (b) characteristics.

Solution

(a) Eq. (2.2): $I_D = \left.\dfrac{E}{R}\right|_{V_D=0\text{ V}} = \dfrac{10\text{ V}}{2\text{ k}\Omega} = 10\text{ mA}$

Eq. (2.3): $V_D = E|_{I_D=0\text{ A}} = 10\text{ V}$

The resulting load line appears in Fig. 2.4. The intersection between the load line and the characteristic curve defines the Q-point as

$$V_{D_Q} \cong \mathbf{0.78\ V}$$

$$I_{D_Q} \cong \mathbf{9.25\ mA}$$

The level of V_D is certainly an estimate, and the accuracy of I_D is limited by the chosen scale. A higher degree of accuracy would require a plot that would be much larger and perhaps unwieldy.

(b) $V_R = I_R R = I_{D_Q} R = (9.25\text{ mA})(1\text{ k}\Omega) = \mathbf{9.25\ V}$

or $V_R = E - V_D = 10\text{ V} - 0.78\text{ V} = \mathbf{9.22\ V}$

The difference in results is due to the accuracy with which the graph can be read. Ideally, the results obtained either way should be the same.

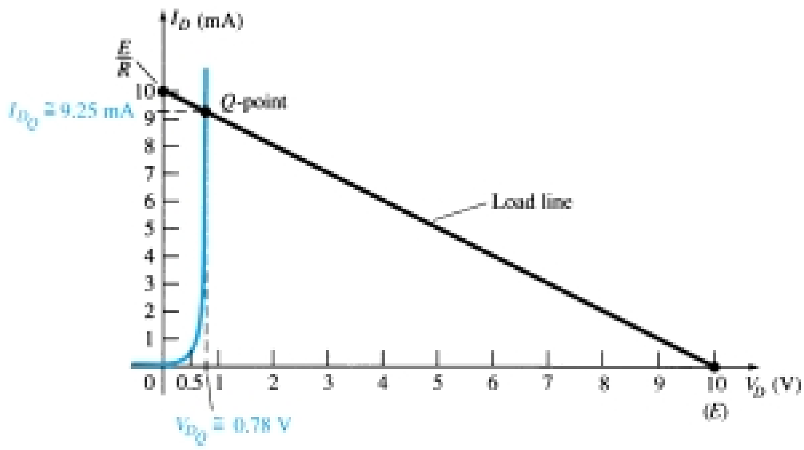


Figure 2.4 Solution to Example 2.1.

EXAMPLE 2.2 Repeat the analysis of Example 2.1 with $R = 2\text{ k}\Omega$.

Solution

(a) Eq. (2.2): $I_D = \left.\dfrac{E}{R}\right|_{V_D=0\text{ V}} = \dfrac{10\text{ V}}{2\text{ k}\Omega} = 5\text{ mA}$

Eq. (2.3): $V_D = E|_{I_D=0\text{ A}} = 10\text{ V}$

The resulting load line appears in Fig. 2.5. Note the reduced slope and levels of diode current for increasing loads. The resulting Q-point is defined by

$$V_{D_Q} \cong \mathbf{0.7\ V}$$

$$I_{D_Q} \cong \mathbf{4.6\ mA}$$

(b) $V_R = I_R R = I_{D_Q} R = (4.6\text{ mA})(2\text{ k}\Omega) = \mathbf{9.2\ V}$

with $V_R = E - V_D = 10\text{ V} - 0.7\text{ V} = \mathbf{9.3\ V}$

The difference in levels is again due to the accuracy with which the graph can be read. Certainly, however, the results provide an expected magnitude for the voltage V_R.

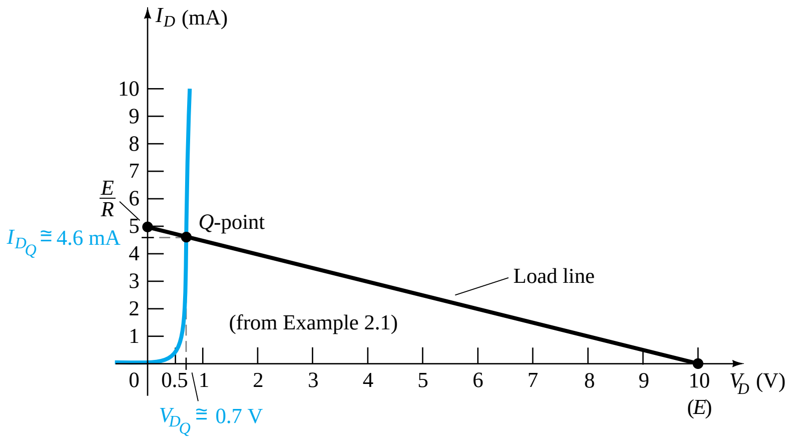


Figure 2.5 Solution to Example 2.2.

As noted in the examples above, the load line is determined solely by the applied network while the characteristics are defined by the chosen device. If we turn to our approximate model for the diode and do not disturb the network, the load line will be exactly the same as obtained in the examples above. In fact, the next two examples repeat the analysis of Examples 2.1 and 2.2 using the approximate model to permit a comparison of the results.

EXAMPLE 2.3

Repeat Example 2.1 using the approximate equivalent model for the silicon semiconductor diode.

Solution

The load line is redrawn as shown in Fig. 2.6 with the same intersections as defined in Example 2.1. The characteristics of the approximate equivalent circuit for the diode have also been sketched on the same graph. The resulting Q-point:

$$V_{D_Q} = \mathbf{0.7\ V}$$

$$I_{D_Q} = \mathbf{9.25\ mA}$$

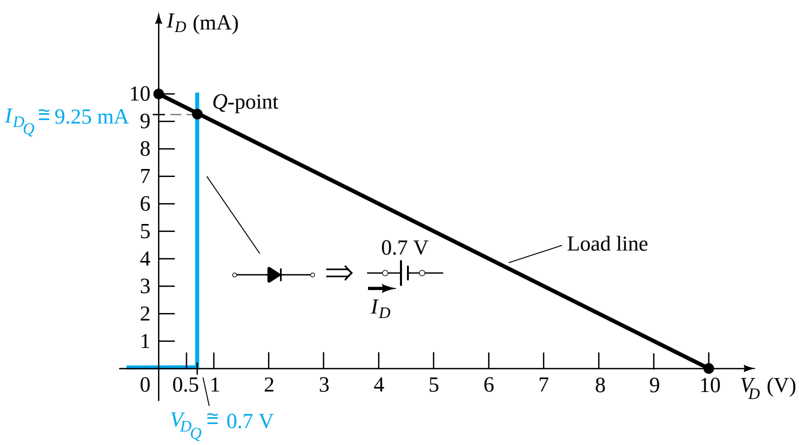


Figure 2.6 Solution to Example 2.1 using the diode approximate model.

The results obtained in Example 2.3 are quite interesting. The level of I_{D_Q} is exactly the same as obtained in Example 2.1 using a characteristic curve that is a great deal easier to draw than that appearing in Fig. 2.4. The level of $V_D = 0.7$ V versus 0.78 V from Example 2.1 is of a different magnitude to the hundredths place, but they are certainly in the same neighborhood if we compare their magnitudes to the magnitudes of the other voltages of the network.

EXAMPLE 2.4

Repeat Example 2.2 using the approximate equivalent model for the silicon semiconductor diode.

Solution

The load line is redrawn as shown in Fig. 2.7 with the same intersections defined in Example 2.2. The characteristics of the approximate equivalent circuit for the diode have also been sketched on the same graph. The resulting *Q*-point:

$$V_{D_Q} = \mathbf{0.7\ V}$$

$$I_{D_Q} = \mathbf{4.6\ mA}$$

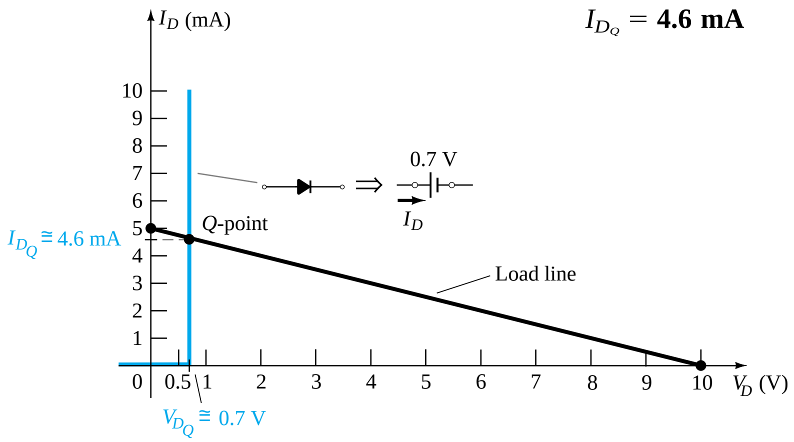


Figure 2.7 Solution to Example 2.2 using the diode approximate model.

In Example 2.4 the results obtained for both V_{D_Q} and I_{D_Q} are the same as those obtained using the full characteristics in Example 2.2. The examples above have demonstrated that the current and voltage levels obtained using the approximate model have been very close to those obtained using the full characteristics. It suggests, as will be applied in the sections to follow, that the use of appropriate approximations can result in solutions that are very close to the actual response with a reduced level of concern about properly reproducing the characteristics and choosing a large-enough scale. In the next example we go a step further and substitute the ideal model. The results will reveal the conditions that must be satisfied to apply the ideal equivalent properly.

EXAMPLE 2.4

Repeat Example 2.1 using the ideal diode model.

Solution

As shown in Fig. 2.8 the load line continues to be the same, but the ideal characteristics now intersect the load line on the vertical axis. The *Q*-point is therefore defined by

$$V_{D_Q} = \mathbf{0\ V}$$

$$I_{D_Q} = \mathbf{10\ mA}$$

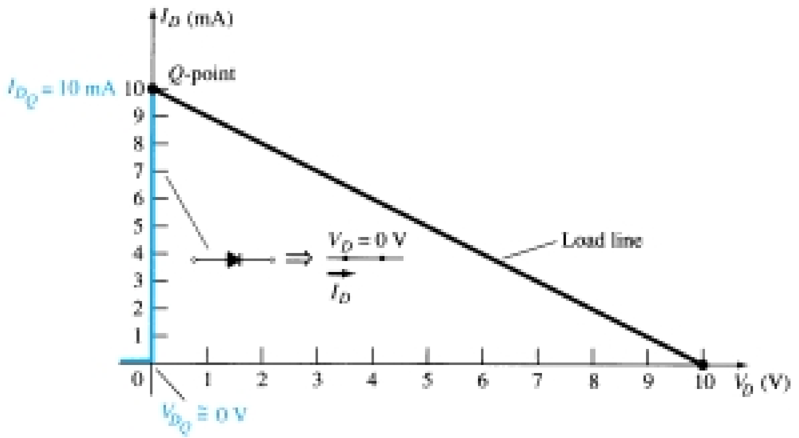


Figure 2.8 Solution to Example 2.1 using the ideal diode model.

The results are sufficiently different from the solutions of Example 2.1 to cause some concern about their accuracy. Certainly, they do provide some indication of the level of voltage and current to be expected relative to the other voltage levels of the network, but the additional effort of simply including the 0.7-V offset suggests that the approach of Example 2.3 is more appropriate.

Use of the ideal diode model therefore should be reserved for those occasions when the role of a diode is more important than voltage levels that differ by tenths of a volt and in those situations where the applied voltages are considerably larger than the threshold voltage V_T. In the next few sections the approximate model will be employed exclusively since the voltage levels obtained will be sensitive to variations that approach V_T. In later sections the ideal model will be employed more frequently since the applied voltages will frequently be quite a bit larger than V_T and the authors want to ensure that the role of the diode is correctly and clearly understood.

2.3 DIODE APPROXIMATIONS

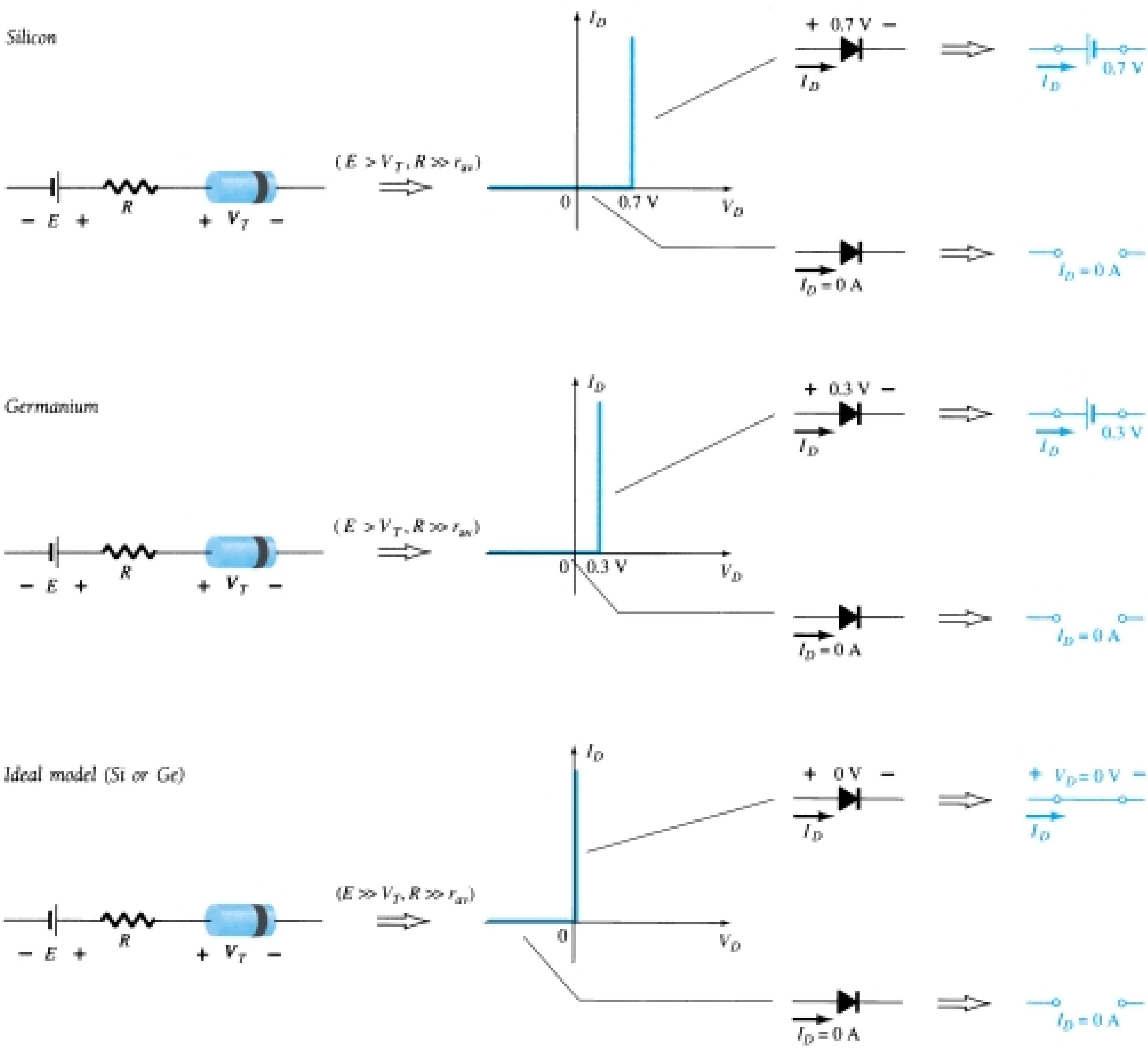
In Section 2.2 we revealed that the results obtained using the approximate piecewise-linear equivalent model were quite close, if not equal, to the response obtained using the full characteristics. In fact, if one considers all the variations possible due to tolerances, temperature, and so on, one could certainly consider one solution to be "as accurate" as the other. Since the use of the approximate model normally results in a reduced expenditure of time and effort to obtain the desired results, it is the approach that will be employed in this book unless otherwise specified. Recall the following:

The primary purpose of this book is to develop a general knowledge of the behavior, capabilities, and possible areas of application of a device in a manner that will minimize the need for extensive mathematical developments.

The complete piecewise-linear equivalent model introduced in Chapter 1 was not employed in the load-line analysis because r_{av} is typically much less than the other series elements of the network. If r_{av} should be close in magnitude to the other series elements of the network, the complete equivalent model can be applied in much the same manner as described in Section 2.2.

In preparation for the analysis to follow, Table 2.1 was developed to review the important characteristics, models, and conditions of application for the approximate and ideal diode models. Although the silicon diode is used almost exclusively due to

TABLE 2.1 Approximate and Ideal Semiconductor Diode Models



its temperature characteristics, the germanium diode is still employed and is therefore included in Table 2.1. As with the silicon diode, a germanium diode is approximated by an open-circuit equivalent for voltages less than V_T. It will enter the "on" state when $V_D \geq V_T = 0.3$ V.

Keep in mind that the 0.7 and 0.3 V in the equivalent circuits are not *independent* sources of energy but are there simply to remind us that there is a "price to pay" to turn on a diode. An isolated diode on a laboratory table will not indicate 0.7 or 0.3 V if a voltmeter is placed across its terminals. The supplies specify the voltage drop across each when the device is "on" and specify that the diode voltage must be at least the indicated level before conduction can be established.

In the next few sections we demonstrate the impact of the models of Table 2.1 on the analysis of diode configurations. For those situations where the approximate equivalent circuit will be employed, the diode symbol will appear as shown in Fig. 2.9a for the silicon and germanium diodes. If conditions are such that the ideal diode model can be employed, the diode symbol will appear as shown in Fig. 2.9b.

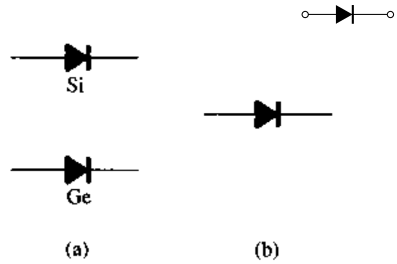


Figure 2.9 (a) Approximate model notation; (b) ideal diode notation.

2.4 SERIES DIODE CONFIGURATIONS WITH DC INPUTS

In this section the approximate model is utilized to investigate a number of series diode configurations with dc inputs. The content will establish a foundation in diode analysis that will carry over into the sections and chapters to follow. The procedure described can, in fact, be applied to networks with any number of diodes in a variety of configurations.

For each configuration the state of each diode must first be determined. Which diodes are "on" and which are "off"? Once determined, the appropriate equivalent as defined in Section 2.3 can be substituted and the remaining parameters of the network determined.

In general, a diode is in the "on" state if the current established by the applied sources is such that its direction matches that of the arrow in the diode symbol, and $V_D \geq 0.7$ V for silicon and $V_D \geq 0.3$ V for germanium.

For each configuration, *mentally* replace the diodes with resistive elements and note the resulting current direction as established by the applied voltages ("pressure"). If the resulting direction is a "match" with the arrow in the diode symbol, conduction through the diode will occur and the device is in the "on" state. The description above is, of course, contingent on the supply having a voltage greater than the "turn-on" voltage (V_T) of each diode.

If a diode is in the "on" state, one can either place a 0.7-V drop across the element, or the network can be redrawn with the V_T equivalent circuit as defined in Table 2.1. In time the preference will probably simply be to include the 0.7-V drop across each "on" diode and draw a line through each diode in the "off" or open state. Initially, however, the substitution method will be utilized to ensure that the proper voltage and current levels are determined.

The series circuit of Fig. 2.10 described in some detail in Section 2.2 will be used to demonstrate the approach described in the paragraphs above. The state of the diode is first determined by mentally replacing the diode with a resistive element as shown in Fig. 2.11. The resulting direction of I is a match with the arrow in the diode symbol, and since $E > V_T$ the diode is in the "on" state. The network is then redrawn as shown in Fig. 2.12 with the appropriate equivalent model for the forward-biased silicon diode. Note for future reference that the polarity of V_D is the same as would result if in fact the diode were a resistive element. The resulting voltage and current levels are the following:

$$\boxed{V_D = V_T} \tag{2.4}$$

$$\boxed{V_R = E - V_T} \tag{2.5}$$

$$\boxed{I_D = I_R = \frac{V_R}{R}} \tag{2.6}$$

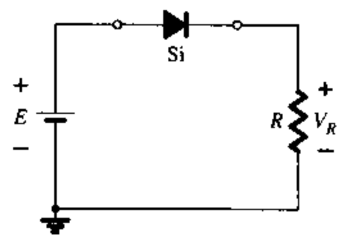


Figure 2.10 Series diode configuration.

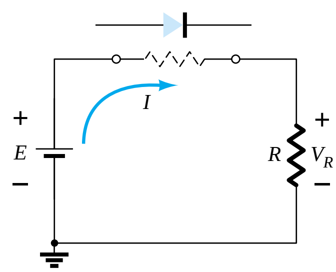


Figure 2.11 Determining the state of the diode of Fig. 2.10.

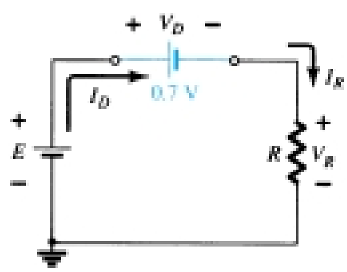


Figure 2.12 Substituting the equivalent model for the "on" diode of Fig. 2.10.