7 IDEAL VERSUS PRACTICAL

In the previous section we found that a *p–n* junction will permit a generous flow of charge when forward-biased and a very small level of current when reverse-biased. Both conditions are reviewed in Fig. 21, with the heavy current vector in Fig. 21a matching the direction of the arrow in the diode symbol and the significantly smaller vector in the opposite direction in Fig. 21b representing the reverse saturation current.

An analogy often used to describe the behavior of a semiconductor diode is a mechanical switch. In Fig. 21a the diode is acting like a closed switch permitting a generous flow of charge in the direction indicated. In Fig. 21b the level of current is so small in most cases that it can be approximated as 0 A and represented by an open switch.

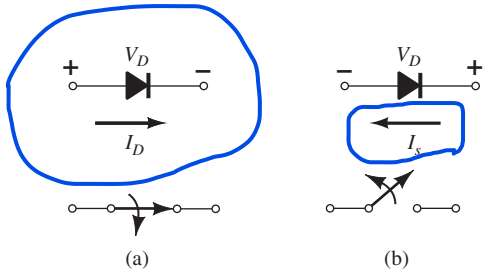


FIG. 21
Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

In other words:

The semiconductor diode behaves in a manner similar to a mechanical switch in that it can control whether current will flow between its two terminals.

However, it is important to also be aware that:

The semiconductor diode is different from a mechanical switch in the sense that when the switch is closed it will only permit current to flow in one direction.

Ideally, if the semiconductor diode is to behave like a closed switch in the forward-bias region, the resistance of the diode should be 0 Ω. In the reverse-bias region its resistance should be ∞Ω to represent the open-circuit equivalent. Such levels of resistance in the forward- and reverse-bias regions result in the characteristics of Fig. 22.

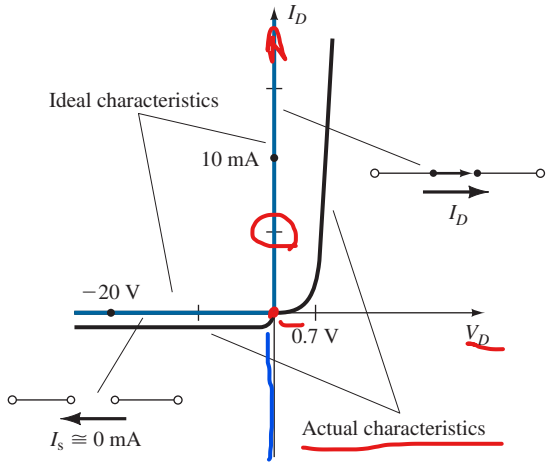


FIG. 22
Ideal versus actual semiconductor characteristics.

The characteristics have been superimposed to compare the ideal Si diode to a real-world Si diode. First impressions might suggest that the commercial unit is a poor impression of the ideal switch. However, when one considers that the only major difference is that the commercial diode rises at a level of 0.7 V rather than 0 V, there are a number of similarities between the two plots.

When a switch is closed the resistance between the contacts is assumed to be 0 Ω. At the plot point chosen on the vertical axis the diode current is 5 mA and the voltage across the diode is 0 V. Substituting into Ohm's law results in

$$R_F = \frac{V_D}{I_D} = \frac{0\text{ V}}{5\text{ mA}} = \mathbf{0\ \Omega} \qquad \text{(short-circuit equivalent)}$$

In fact:

At any current level on the vertical line, the voltage across the ideal diode is 0 V and the resistance is 0 Ω.

For the horizontal section, if we again apply Ohm's law, we find

$$R_R = \frac{V_D}{I_D} = \frac{20\text{ V}}{0\text{ mA}} \cong \infty\,\Omega \qquad \text{(open-circuit equivalent)}$$

Again:

Because the current is 0 mA anywhere on the horizontal line, the resistance is considered to be infinite ohms (an open-circuit) at any point on the axis.

Due to the shape and the location of the curve for the commercial unit in the forward-bias region there will be a resistance associated with the diode that is greater than 0 Ω. However, if that resistance is small enough compared to other resistors of the network in series with the diode, it is often a good approximation to simply assume the resistance of the commercial unit is 0 Ω. In the reverse-bias region, if we assume the reverse saturation current is so small it can be approximated as 0 mA, we have the same open-circuit equivalence provided by the open switch.

The result, therefore, is that there are sufficient similarities between the ideal switch and the semiconductor diode to make it an effective electronic device. In the next section the various resistance levels of importance are determined for use in the chapter "Diode Applications", where the response of diodes in an actual network is examined.

8 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, which 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. 23 and applying the following equation:

$$R_D = \frac{V_D}{I_D} \qquad \textbf{(4)}$$

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).

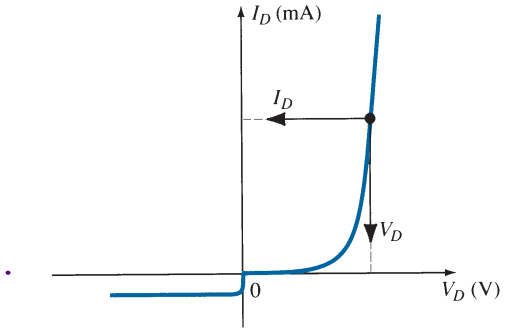


FIG. 23
Determining the dc resistance of a diode at a particular operating point.

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

Typically, the dc resistance of a diode in the active (most utilized) will range from about 10 Ω to 80 Ω.

EXAMPLE 3 Determine the dc resistance levels for the diode of Fig. 24 at

a. $I_D = 2$ mA (low level)
b. $I_D = 20$ mA (high level)
c. $V_D = -10$ V (reverse-biased)

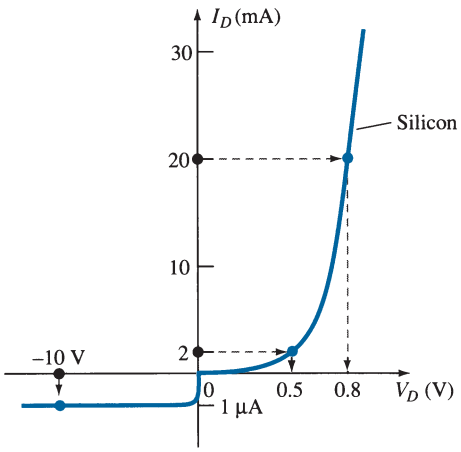


FIG. 24
Example 3.

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

Eq. (4) and Example 3 reveal 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 a 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. 25. With no applied varying signal, the point of operation would be the *Q*-point appearing on Fig. 25, determined by the applied dc levels. The designation *Q-point* is derived from the word *quiescent*, which means "still or unvarying."

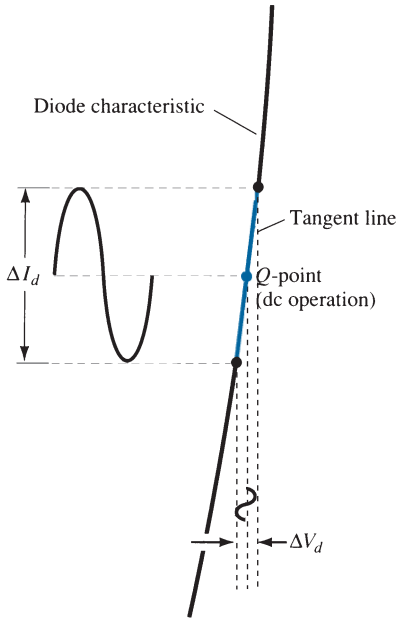


FIG. 25
Defining the dynamic or ac resistance.

A straight line drawn tangent to the curve through the *Q*-point as shown in Fig. 26 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,

$$r_d = \frac{\Delta V_d}{\Delta I_d} \qquad \textbf{(5)}$$

where Δ signifies a finite change in the quantity.

The steeper the slope, the lower is the value of ΔV_d for the same change in ΔI_d and the lower is the resistance. The ac resistance in the vertical-rise region of the characteristic is therefore quite small, whereas 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 is the ac resistance.

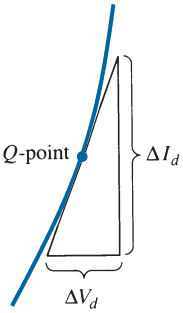


FIG. 26
Determining the ac resistance at a Q-point.

EXAMPLE 4 For the characteristics of Fig. 27:

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.

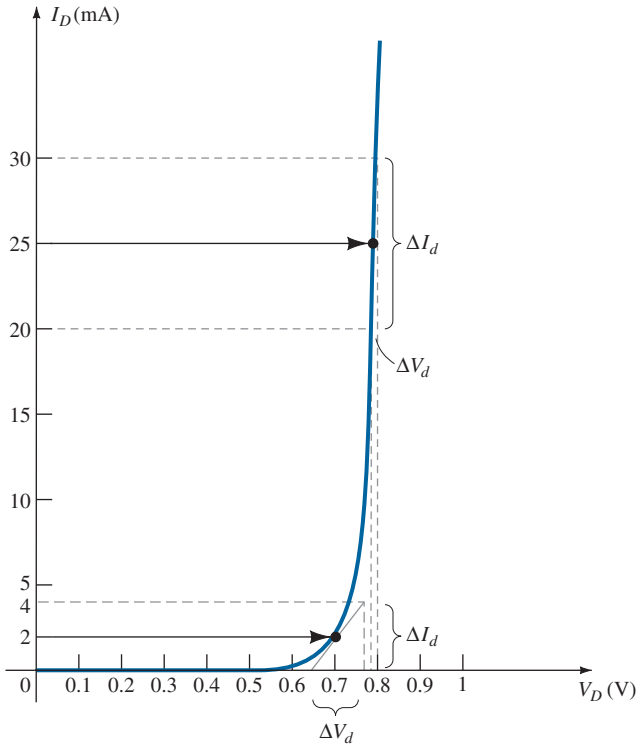


FIG. 27
Example 4.

Solution:

a. For $I_D = 2$ mA, the tangent line at $I_D = 2$ mA was drawn as shown in Fig. 27 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, respectively,

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

and

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

and the ac resistance is

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

b. For $I_D = 25$ mA, the tangent line at $I_D = 25$ mA was drawn as shown in Fig. 27 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, respectively,

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

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 that states:

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

Equation (5), as defined by Fig. 26, is, therefore, essentially finding the derivative of the function at the *Q*-point of operation. If we find the derivative of the general equation (2) 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. (2) with respect to the applied bias will result in

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}\left[I_s(e^{V_D/nV_T} - 1)\right]$$

and

$$\frac{dI_D}{dV_D} = \frac{1}{nV_T}(I_D + I_s)$$

after we apply differential calculus. In general, $I_D \gg I_s$ in the vertical-slope section of the characteristics and

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

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

$$\frac{dV_D}{dI_D} = r_d = \frac{nV_T}{I_D}$$

Substituting $n = 1$ and $V_T \cong 26$ mV from Example 1 results in

$$\boxed{r_d = \frac{26\text{ mV}}{I_D}} \qquad \textbf{(6)}$$

The significance of Eq. (6) 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. (5). It is important to keep in mind, however, that Eq. (6) is accurate only for values of I_D in the vertical-rise section of the curve. For lesser values of I_D, $n = 2$ (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. (6) 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. (6) by adding a resistance denoted r_B:

$$\boxed{r'_d = \frac{26\text{ mV}}{I_D} + r_B}\ \text{ohms} \qquad \textbf{(7)}$$

The resistance r'_d, therefore, includes the dynamic resistance defined by Eq. (6) and the resistance r_B just introduced. 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 4 the ac resistance at 25 mA was calculated to be 2 Ω. Using Eq. (6), 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 4 the ac resistance at 2 mA was calculated to be 27.5 Ω. Using Eq. (6) but multiplying by a factor of 2 for this region (in the knee of the curve $n = 2$),

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

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. (5) is a difficult process at best and the results have to be treated with skepticism. 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 text 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 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. (5) is sufficiently high to permit the open-circuit approximation.

Typically, the ac resistance of a diode in the active region will range from about 1 Ω to 100 Ω.

Average AC Resistance

If the input signal is sufficiently large to produce a broad swing such as indicated in Fig. 28, the resistance associated with the device for this region is called the *average ac resistance*. The average ac resistance is, by definition, the resistance determined by a straight line drawn between the two intersections established by the maximum and minimum values of input voltage. In equation form (note Fig. 28),

$$r_{\text{av}} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt. to pt.}} \tag{8}$$

For the situation indicated by Fig. 28,

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

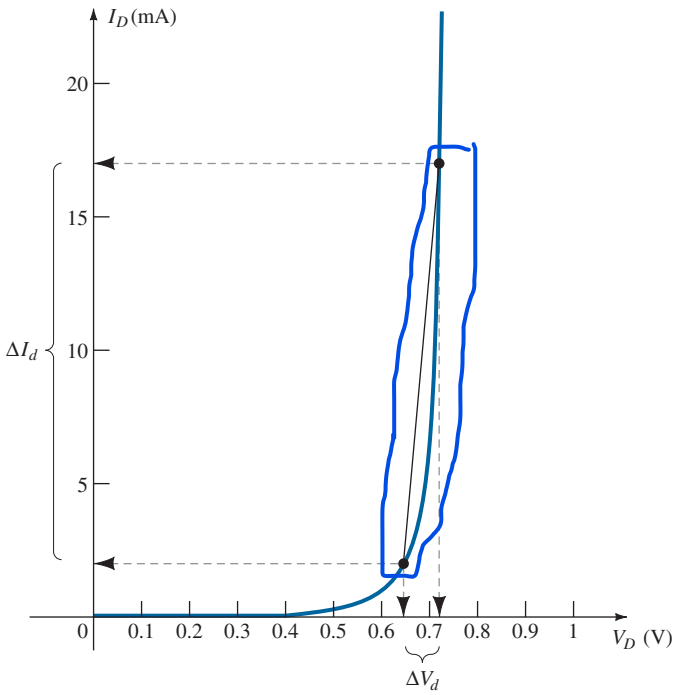


FIG. 28
Determining the average ac resistance between indicated limits.

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

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

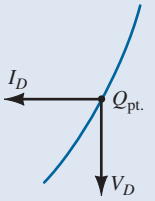
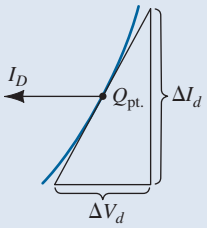
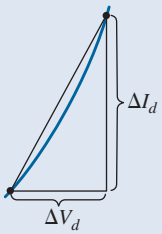
If the ac resistance (r_d) were determined at $I_D = 2$ mA, its value would be more than 5 Ω, and if determined at 17 mA, it would be less. In between, the ac resistance would make the transition from the high value at 2 mA to the lower value at 17 mA. Equation (7) defines a value that is considered the average of the ac values from 2 mA 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 is the resistance level.

Summary Table

Table 6 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.

TABLE 6
Resistance Levels

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

9 DIODE EQUIVALENT CIRCUITS

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device or system 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. 29. The resulting equivalent circuit is called a *piecewise-linear equivalent circuit*. It should be obvious from Fig. 29 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 8 is the resistance level appearing in the equivalent circuit of Fig. 28 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 result 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. 29), a battery V_K opposing the conduction direction must appear in the equivalent circuit as shown in Fig. 30. 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}.

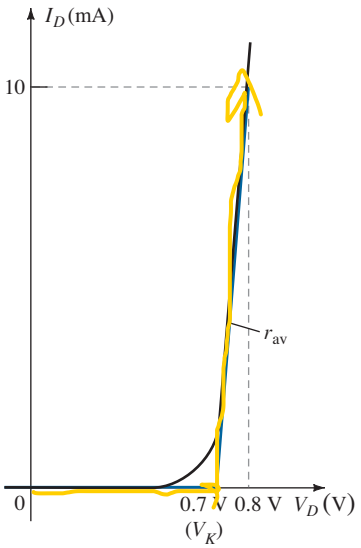


FIG. 29
Defining the piecewise-linear equivalent circuit using straight-line segments to approximate the characteristic curve.

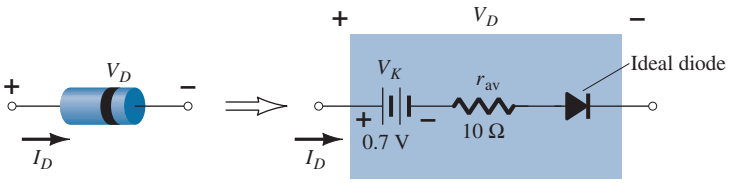


FIG. 30
Components of the piecewise-linear equivalent circuit.

Keep in mind, however, that V_K in the equivalent circuit is not an independent voltage source. If a voltmeter is placed across an isolated diode on the top of a laboratory 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 10). 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 that for silicon a shift of 0.7 V is required before the characteristics rise, and we obtain

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

as obtained for Fig. 29.

If the characteristics or specification sheet for a diode is not available the resistance r_{av} can be approximated by the ac resistance r_d.

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. Removing r_{av} from the equivalent circuit is the same as implying that the characteristics of the diode appear as shown in Fig. 31. Indeed, this approximation is frequently employed in semiconductor circuit analysis. 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).

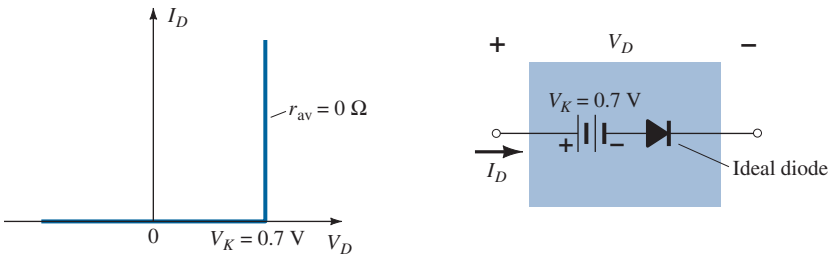


FIG. 31
Simplified equivalent circuit for the silicon semiconductor diode.

Ideal Equivalent Circuit

Now that r_{av} has been removed from the equivalent circuit, let us take the analysis 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. 32 with its characteristics.

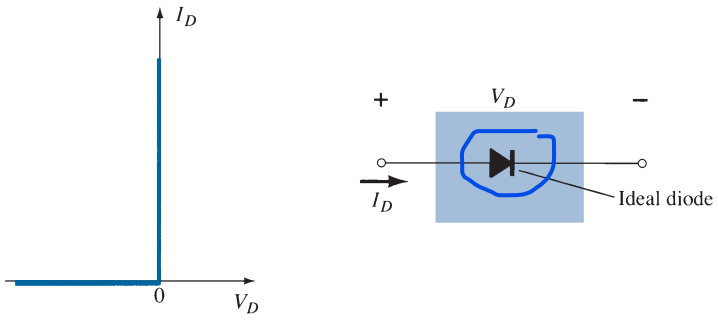


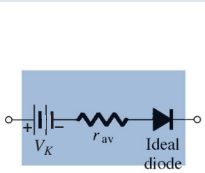
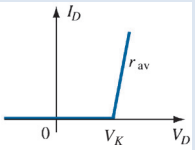
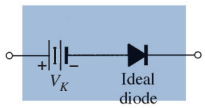
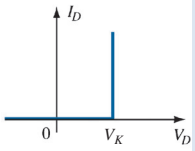
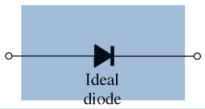
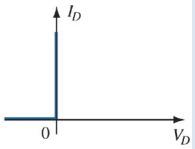
FIG. 32
Ideal diode and its characteristics.

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.

Summary Table

For clarity, the diode models employed for the range of circuit parameters and applications are provided in Table 7 with their piecewise-linear characteristics. There are always exceptions to the general rule, but it is fairly safe to say that the simplified equivalent model will

TABLE 7
Diode Equivalent Circuits (Models)

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

be employed most frequently in the analysis of electronic systems, whereas the ideal diode is frequently applied in the analysis of power supply systems where larger voltages are encountered.

10 TRANSITION AND DIFFUSION CAPACITANCE

It is important to realize that:

Every electronic or electrical device is frequency sensitive.

That is, the terminal characteristics of any device will change with frequency. Even the resistance of a basic resistor, as of any construction, will be sensitive to the applied frequency. At low to mid-frequencies most resistors can be considered fixed in value. However, as we approach high frequencies, stray capacitive and inductive effects start to play a role and will affect the total impedance level of the element.

For the diode it is the stray capacitance levels that have the greatest effect. At low frequencies and relatively small levels of capacitance the reactance of a capacitor, determined by $X_C = 1/2\pi fC$, is usually so high it can be considered infinite in magnitude, represented by an open circuit, and ignored. At high frequencies, however, the level of X_C can drop to the point where it will introduce a low-reactance "shorting" path. If this shorting path is across the diode, it can essentially keep the diode from affecting the response of the network.

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.

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 a diode the depletion region (free of carriers) 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. 33. The fact that the capacitance is dependent on the applied reverse-bias potential has application in a number of electronic systems.

This capacitance, called the transition (C_T), barriers, or depletion region capacitance, is determined by

$$C_T = \frac{C(0)}{(1 + |V_R/V_K|)^n} \tag{9}$$