Electronic Devices

Course Teacher
Niloy Goswami

Prepared By
Dr. Md. Kabiruzzaman

Reference book:

Electronic Devices and Circuit Theory (Chapter-1)

Robert L. Boylestad and L. Nashelsky , (11th Edition)

Department of Electrical and Electronics Engineering
American International University-Bangladesh(AIUB)

Objectives

- **Develop a clear understanding of the basic operation and characteristics of a diode in the no-bias, forward-bias, and reverse-bias regions.**
- **Be able to calculate the dc, ac, and average ac resistance of a diode from the characteristics.**
- **Understand the impact of an equivalent circuit whether it is ideal or practical.**
- **Become familiar with the operation and characteristics of a Zener diode and light- emitting diode.**

Semiconductor Diode: No Applied Bias (V=0 V)

❖ **Now that both n – and p -type materials are available, we can construct our first solid-state electronic device: The semiconductor diode , with applications too numerous to mention, is created by simply joining an n -type and a p -type material together.**

❖ ***In the absence of an applied bias*** **across a semiconductor diode,** ***the net flow of charge in one direction is zero.***

No Applied Bias (V_D=0 V)

- The region of uncovered positive and negative ions is called the depletion region due to the depletion of free charge carriers

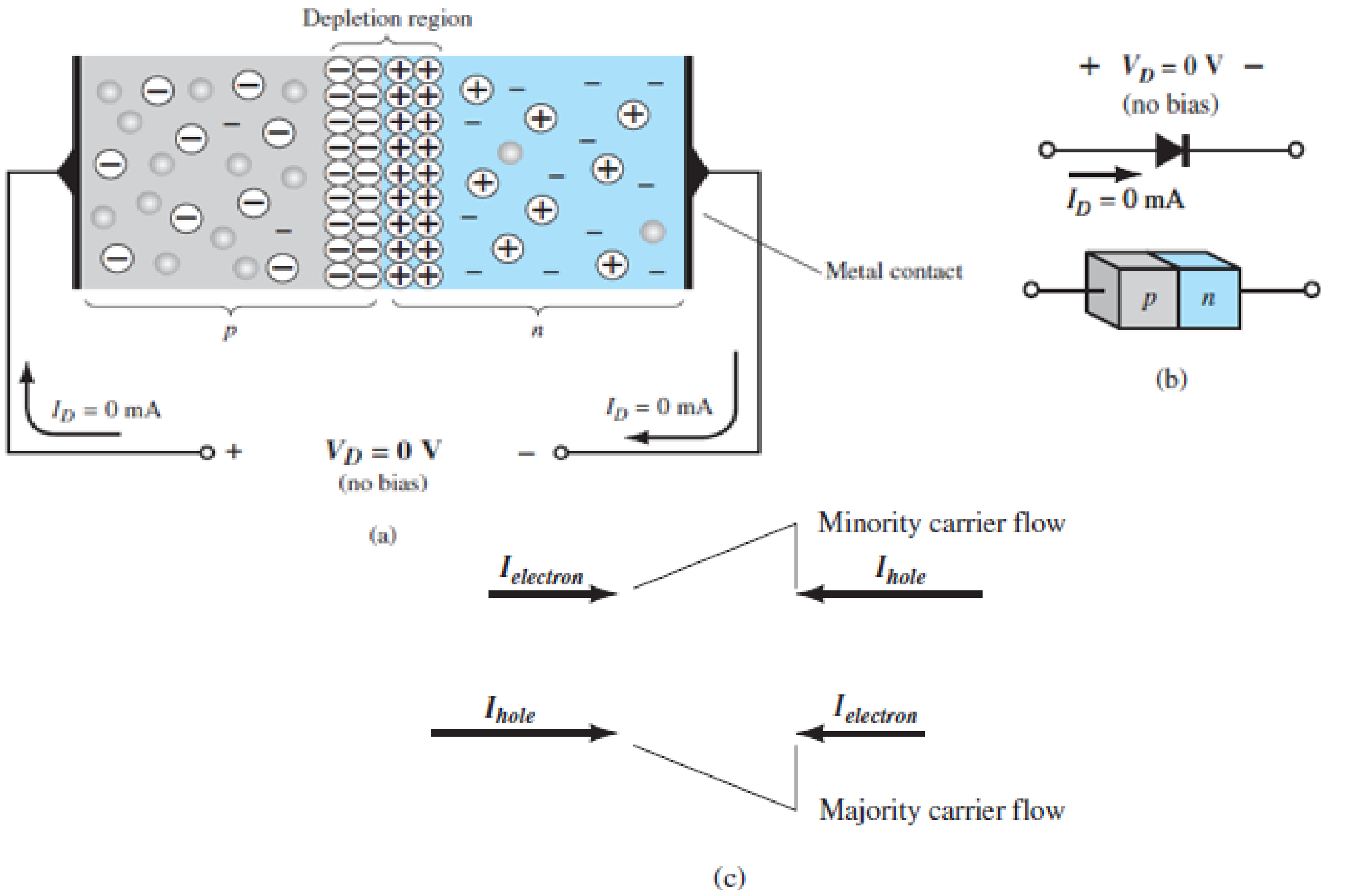


FIG. 1.12

A p–n junction with no external bias: (a) an internal distribution of charge; (b) a diode symbol, with the defined polarity and the current direction; (c) demonstration that the net carrier flow is zero at the external terminal of the device when V_D = 0 V.

Reverse-Bias Condition (V_D<0 V)

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

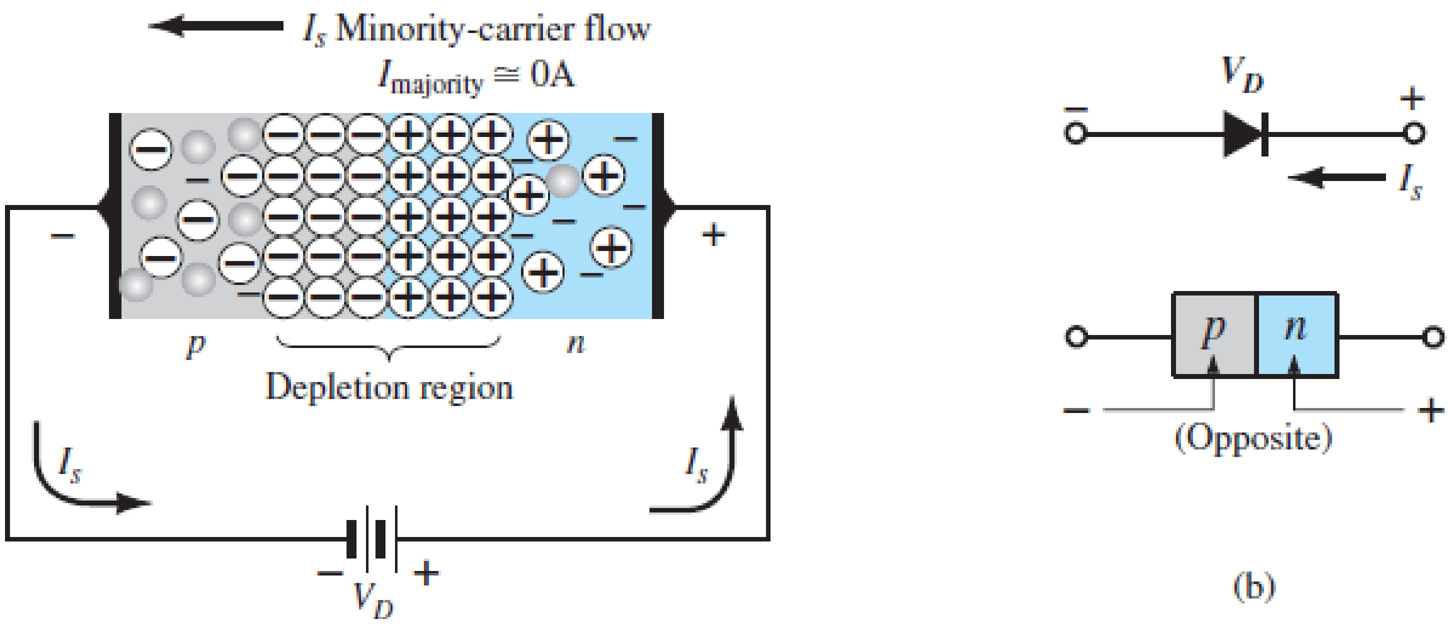


FIG. 1.13

Reverse-biased p–n junction: (a) internal distribution of charge under reverse-bias conditions; (b) reverse-bias polarity and direction of reverse saturation current.

Forward-Bias Condition (V_D>0 V)

A *forward-bias* or "on" condition is established by applying the positive potential to the *p* -type material and the negative potential to the *n* -type material as shown in Fig. 1.14 .

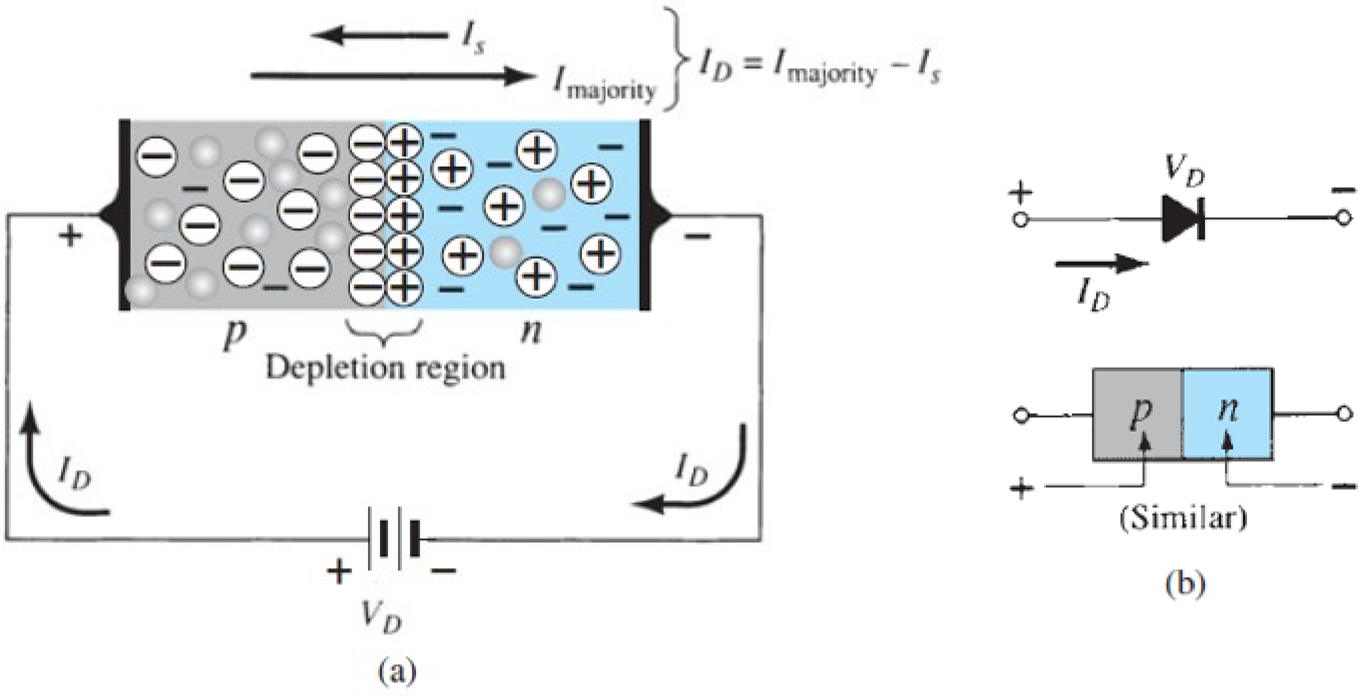


FIG. 1.14

Forward-biased p–n junction: (a) internal distribution of charge under forward-bias conditions; (b) forward-bias polarity and direction of resulting current.

Forward-Bias Condition (V_D>0 V) Contd.

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

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)} \quad \text{(A)}$$

Where, I_s is the reverse saturation current

V_D is the applied forward-bias voltage across the diode

n is an ideality factor, which is a function of the ***operating conditions and physical construction***; it has a range between 1 and 2 depending on a wide variety of factors (n = 1 will be assumed throughout this text unless otherwise noted).

Forward-Bias Condition (V_D>0 V) Contd.

- The voltage V_T in Eq. (1.1) is called the thermal voltage and is determined by:

$$\boxed{V_T = \frac{kT_K}{q}} \quad \text{(V)}$$

where k is Boltzmann's constant = 1.38 * 10^{-23} J/K

T_K is the absolute temperature in kelvins = 273 + the temperature in °C

q is the magnitude of electronic charge = 1.6 * 10^{-19} C

EXAMPLE 1.1 At a temperature of 27°C (common temperature for components in an enclosed operating system), determine the thermal voltage V_T.

Solution: Substituting into Eq. (1.3), we obtain

$$T = 273 + {}^\circ\mathrm{C} = 273 + 27 = 300\ \mathrm{K}$$

$$V_T = \frac{kT_K}{q} = \frac{(1.38 \times 10^{-23}\ \mathrm{J/K})(30\ \mathrm{K})}{1.6 \times 10^{-19}\ \mathrm{C}}$$

$$= 25.875\ \mathrm{mV} \cong 26\ \mathrm{mV}$$

The thermal voltage will become an important parameter in the analysis to follow in this chapter and a number of those to follow.

Semiconductor Diode Characteristics

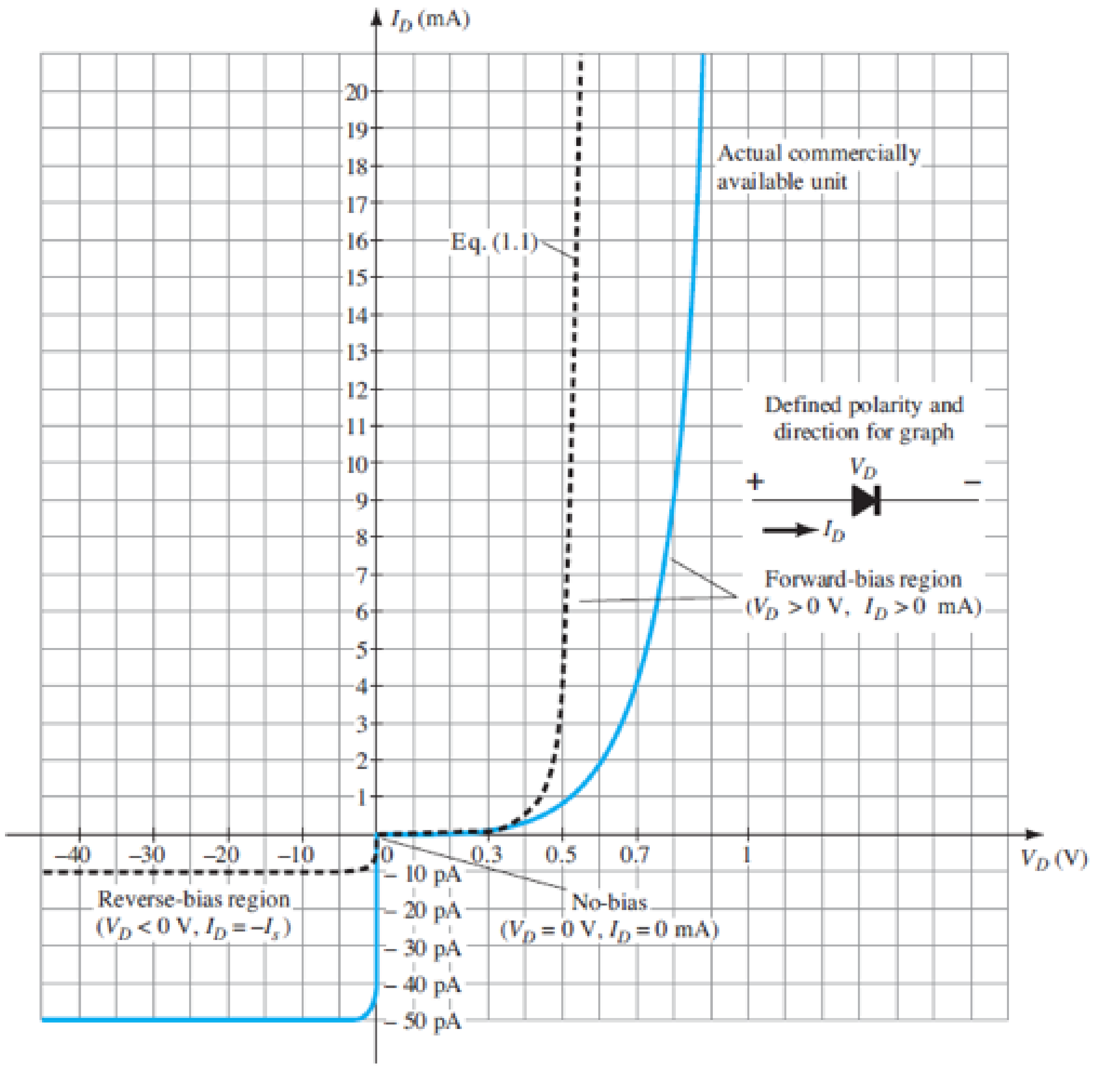


FIG. 1.15
Silicon semiconductor diode characteristics.

Breakdown Region

- The maximum reverse-bias potential that can be applied before entering the breakdown region is called the ***peak inverse voltage*** (referred to simply as the PIV rating) or the peak reverse voltage (denoted the PRV rating).
- If an application requires a PIV rating greater than that of a single unit, a number of diodes of the same characteristics can be connected in series. Diodes are also connected in parallel to increase the current-carrying capacity.
- In general, the breakdown voltage of GaAs diodes is about 10% higher those for silicon diodes but after 200% higher than levels for Ge diodes.

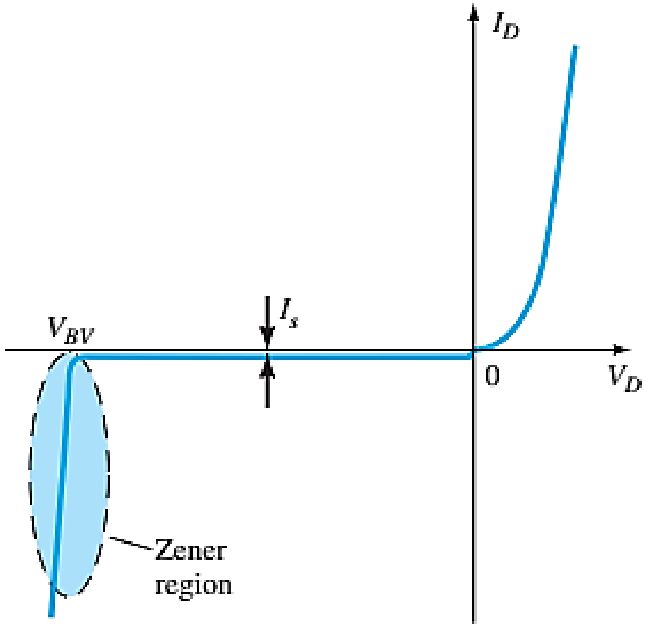


FIG. 1.17
Breakdown region.

Breakdown Region Contd.

- As the voltage across the diode increases in the reverse-bias region, the velocity of the minority carriers responsible for the reverse saturation current I_s will also increase.

- Eventually, their velocity and associated kinetic energy (**$W_K = 1/2\ mv^2$**) will be sufficient to release additional carriers through collisions with otherwise stable atomic structures.

- An ionization process will result whereby valence electrons absorb sufficient energy to leave the parent atom.

- These additional carriers can then aid the ionization process to the point where a high avalanche current is established and the ***avalanche breakdown*** region determined.

Breakdown Region Contd.

- The avalanche region (V_{BV}) can be brought closer to the vertical axis by increasing the doping levels in the p- and n-type materials.

- However, as V_{BV} decreases to very low levels, such as -5 V, another mechanism, called ***Zener breakdown***, will contribute to the sharp change in the characteristic.

- It occurs because there is a strong electric field in the region of the junction that can disrupt the bonding forces within the atom and "generate" carriers.

- Although the Zener breakdown mechanism is a significant contributor only at lower levels of V_{BV}, this sharp change in the characteristic at any level is called the ***Zener region***, and diodes employing this unique portion of the characteristic of a p–n junction are called Zener diodes.

Ge, Si & GaAs

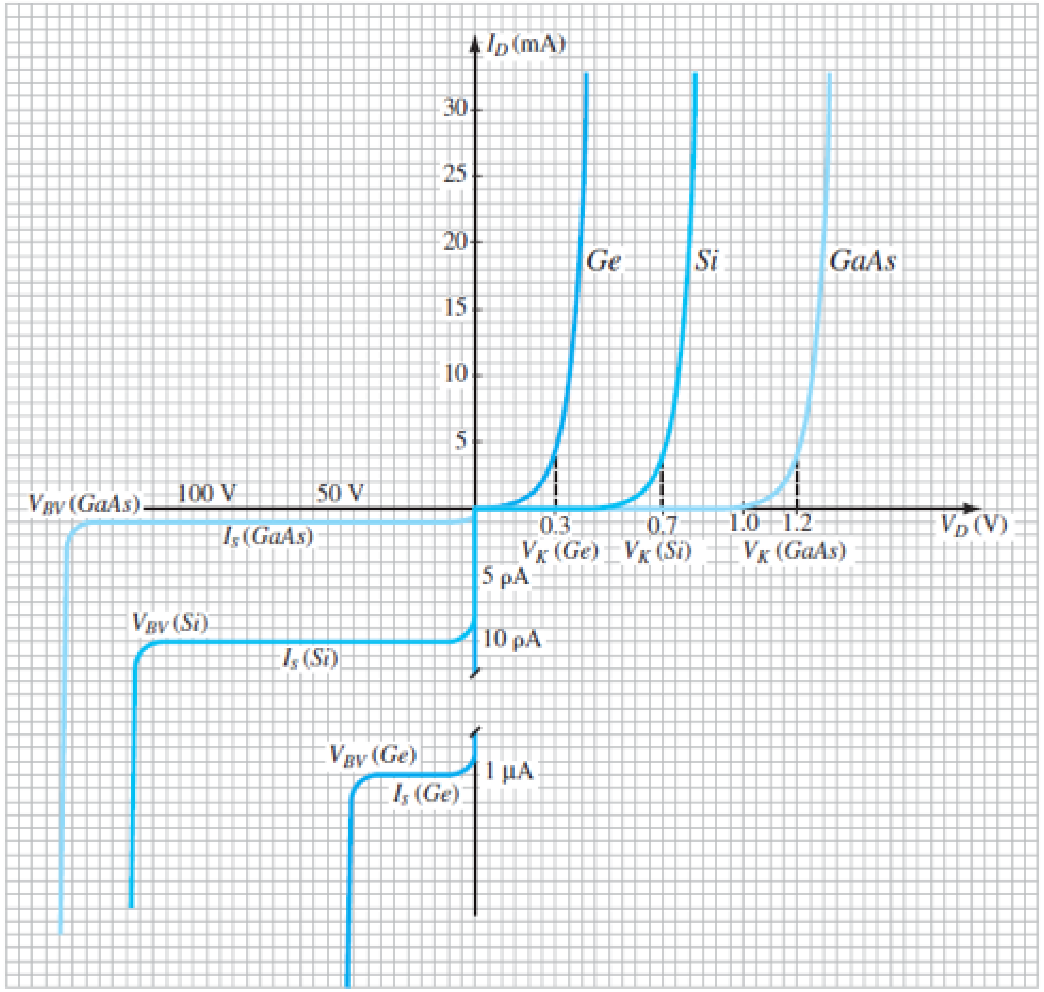


FIG. 1.18
Comparison of Ge, Si, and GaAs commercial diodes.

TABLE 1.3
Knee Voltages V_K

Semiconductor	V_K(V)
Ge	0.3
Si	0.7
GaAs	1.2

Temperature Effects

- **In the forward-bias region the characteristics of a silicon diode shift to the left at a rate of 2.5 mV per centigrade degree increase in temperature.**
- **In the reverse-bias region the reverse current of a silicon diode doubles for every 10°C rise in temperature.**
- **The reverse breakdown voltage of a semiconductor diode will increase or decrease with temperature.**
- **As temperature increases it adds energy to the diode:**
    - **It reduces the required forward bias voltage for forward bias conduction.**
    - **It increases the amount of reverse current in the reverse bias condition.**
    - **It increases maximum reverse bias avalanche voltage.**
- **Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.**

Temperature Effect Contd.

In the forward-bias region the characteristics of a silicon diode shift to the left at a rate of 2.5 mV per centigrade degree increase in temperature.

In the reverse-bias region the reverse current of a silicon diode doubles for every 10°C rise in temperature.

Finally, The reverse breakdown voltage of a semiconductor diode will increase or decrease with temperature.

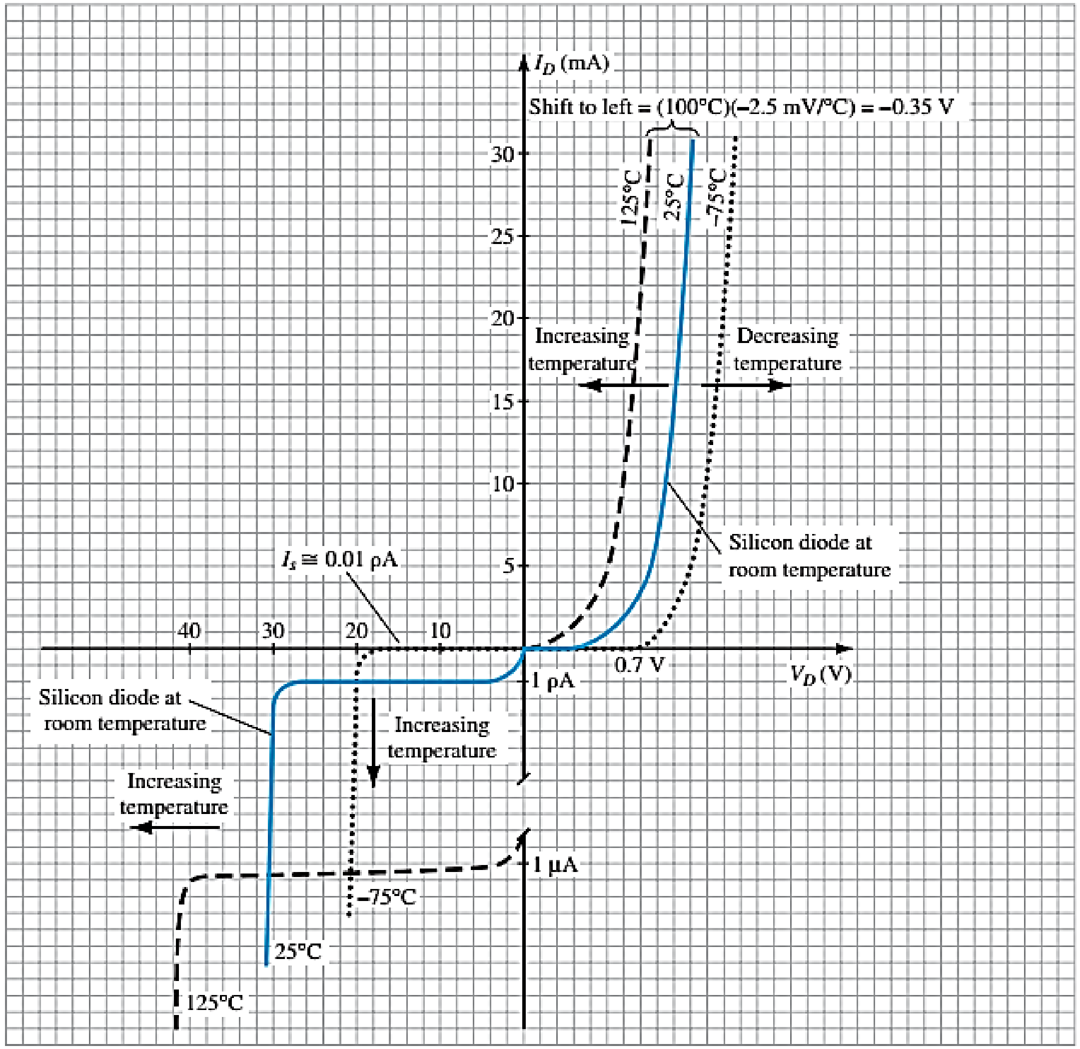


FIG. 1.19
Variation in Si diode characteristics with temperature change.

Ideal vs Practical

- **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.**

- **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.**

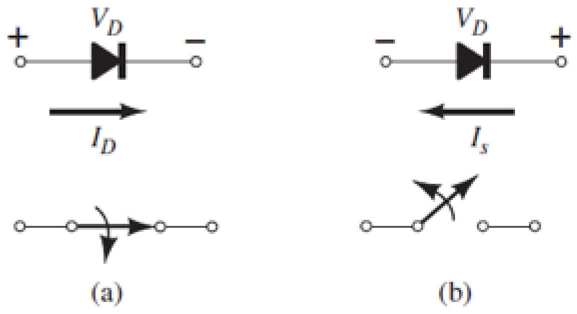


FIG. 1.21
Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

Ideal vs Practical Contd.

- 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.

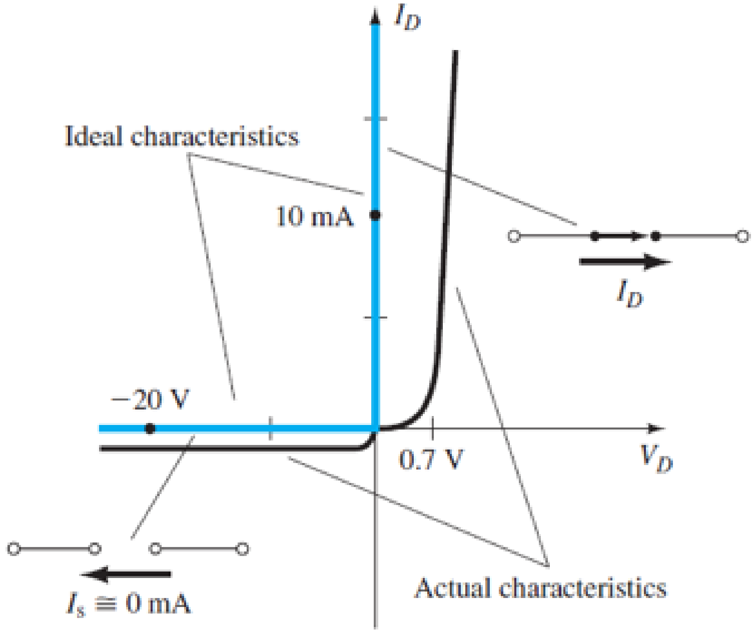


FIG. 1.22
Ideal versus actual semiconductor characteristics.

Resistance Levels

- **Semiconductors react differently to DC and AC currents.**

- **There are three types of resistance:**
  - **DC (static) resistance**
  - **AC (dynamic) resistance**
  - **Average AC resistance**

DC or Static Resistance

- **For a specific applied DC voltage $V_{D,}$ the diode has a specific current I_{D}, and a specific resistance R_{D}.**

$$\boxed{R_D = \frac{V_D}{I_D}}$$

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

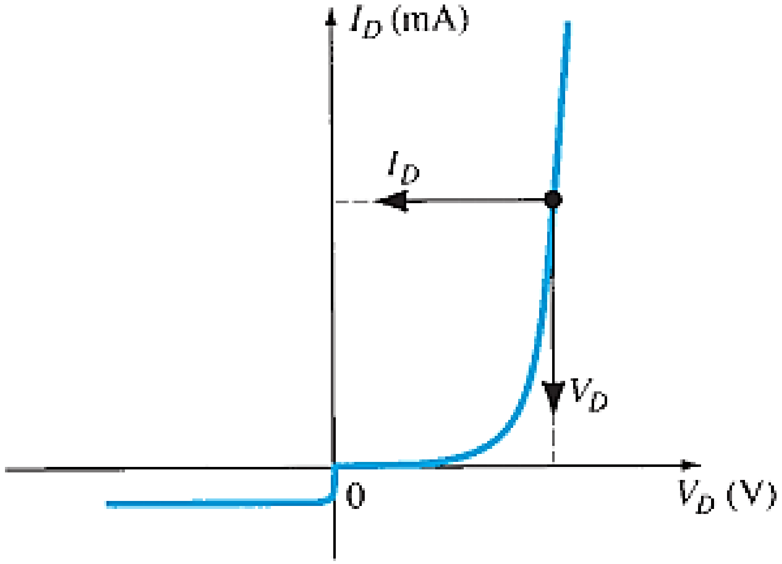


FIG. 1.23
Determining the dc resistance of a diode at a particular operating point.

EXAMPLE 1.3 Determine the dc resistance levels for the diode of Fig. 1.24 at

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

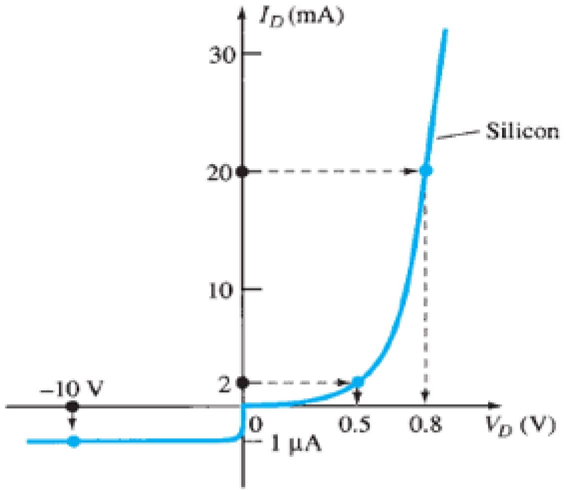


FIG. 1.24
Example 1.3.

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

- **The dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest.**
- **The designation Q-point is derived from the word quiescent, which means “still or unvarying.”**
- **In general, therefore, the lower the Q-point of operation (smaller current or lower voltage), the higher is the ac resistance.**
- ***See Example 1.4.***

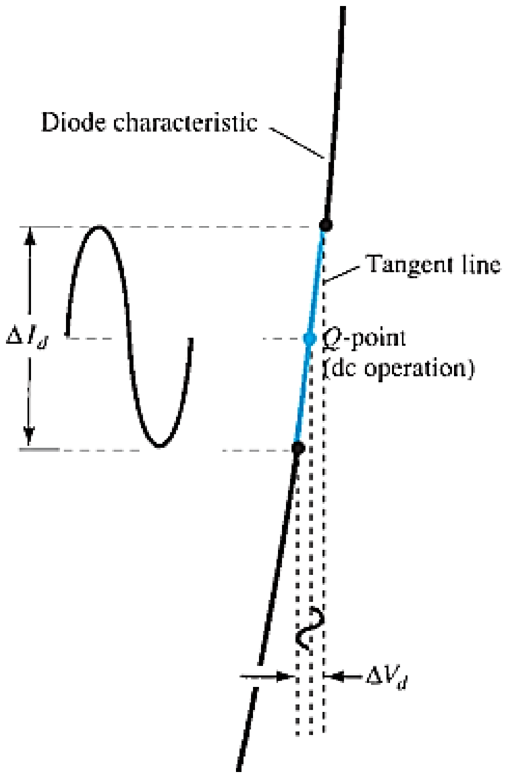


FIG. 1.25
Defining the dynamic or ac resistance.

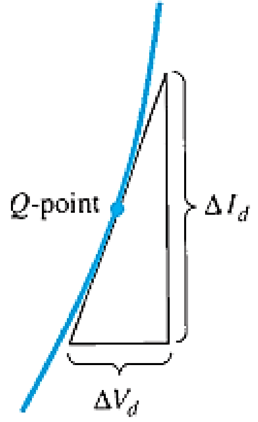


FIG. 1.26
Determining the ac resistance at a Q-point.

AC or Dynamic Resistance Contd.

- **In the forward bias region:**

$$\boxed{r'_d = \frac{26\ \text{mV}}{I_D} + r_B} \quad \text{ohms}$$

- **The resistance depends on the amount of current (I_D) in the diode.**
- **The voltage across the diode is fairly constant (26 mV for 25°C).**
- **r_B ranges from a typical 0.1 Ω for high power devices to 2 Ω for low power, general purpose diodes. In some cases r_B can be ignored.**
- **In the reverse bias region:** $r'_d = \infty$

The resistance is effectively infinite. The diode acts like an open.

Average AC or 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.**

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

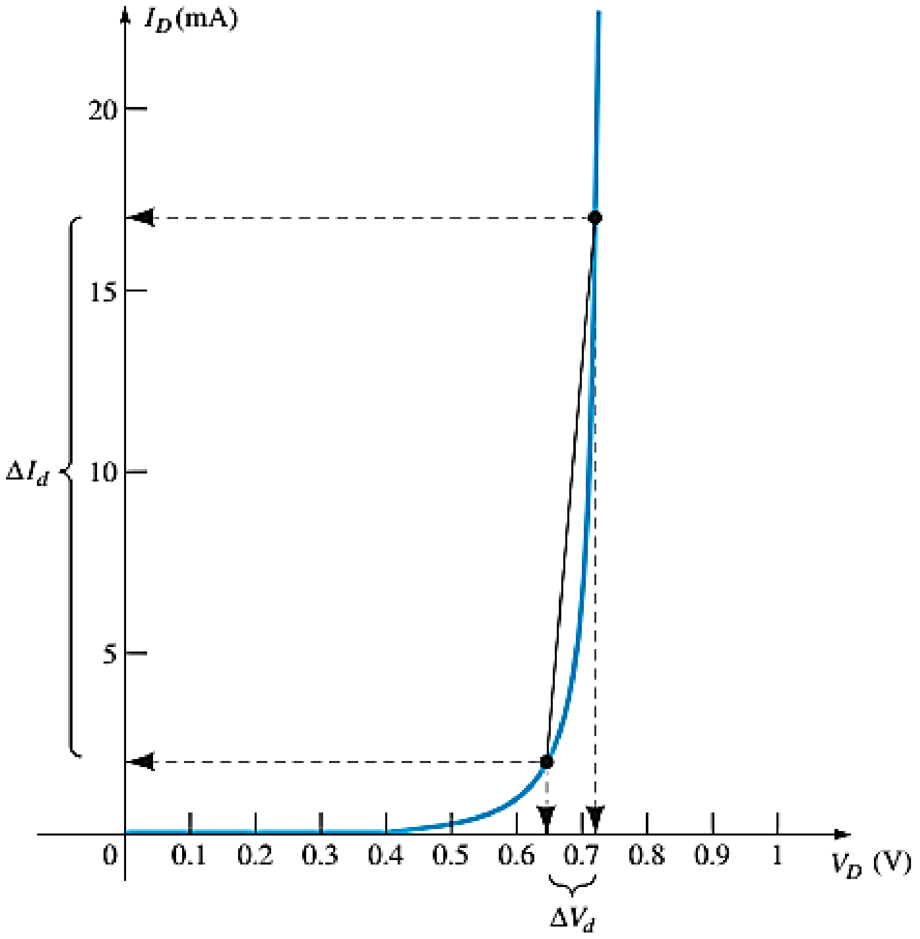
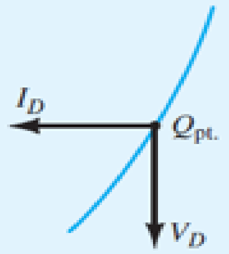
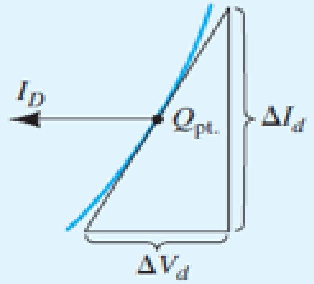
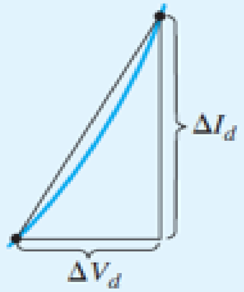


FIG. 1.28
Determining the average ac resistance between indicated limits.

Summary table

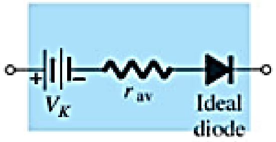
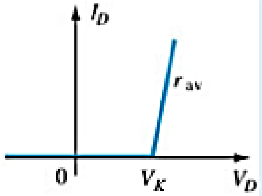
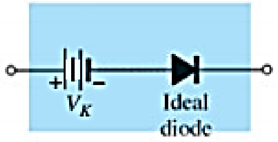
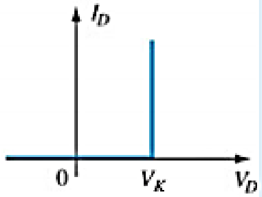
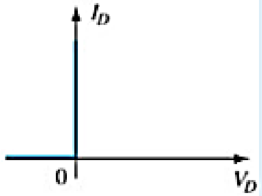
TABLE 1.6
Resistance Levels

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

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.

TABLE 1.7
Diode Equivalent Circuits (Models)

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

Thank You