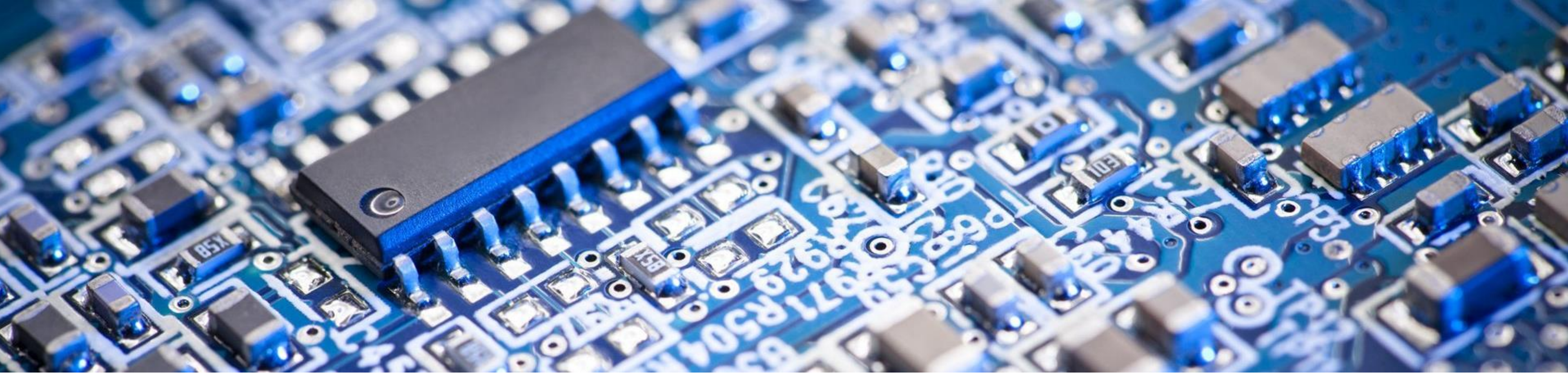


Semiconductor Diodes

Prepared By:

Dr. Md. Rifat Hazari

Assistant Professor

Department of Electrical and Electronic Engineering

Email: rifat@aiub.edu

Office# D Building (5th Floor)

Faculty of Engineering

American International University-Bangladesh

Chapter 1

Reference book: Electronic Devices and Circuit Theory

(11th Edition) Robert F. Boylestad

Objectives

- **Become aware of the general characteristics of three important semiconductor materials: Si, Ge, GaAs.**
- **Understand conduction using electron and hole theory.**
- **Be able to describe the difference between *n* – and *p* -type materials.**
- **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.**

Introduction

One of the noteworthy things about this field, as in many other areas of technology, is how little the fundamental principles change over time. Systems are incredibly smaller, current speeds of operation are truly remarkable, and new gadgets surface every day, leaving us to wonder where technology is taking us.

- The miniaturization that has occurred in recent years leaves us to wonder about its limits.
- Complete systems now appear on wafers thousands of times smaller than the single element of earlier networks.
- The first integrated circuit (IC) was developed by Jack Kilby while working at Texas Instruments in 1958.

Figure 1.1: Jack St. Clair Kilby, inventor of the integrated circuit and co-inventor of the electronic handheld calculator.
(Courtesy of Texas Instruments.)

Introduction Contd.

- Today, the Intel® Core™ i7 Extreme Edition Processor of Fig. 1.2 has 731 million transistors in a package that is only slightly larger than a 1.67 sq. inches.

- In 1965, Dr. Gordon E. Moore presented a paper predicting that the transistor count in a single IC chip would double every two years.

- Now, more than 45 years, later we find that his prediction is amazingly accurate and expected to continue for the next few decades.

Figure 1.2: Intel® Core™ i7 Extreme Edition Processor.

Semiconductor Materials: Ge, SI & GaAs

- The construction of every discrete (individual) solid-state (hard crystal structure) electronic device or integrated circuit begins with a semiconductor material of the highest quality.
- Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.
- In general, semiconductor materials fall into one of two classes: single-crystal and compound.
- Single-crystal semiconductors such as germanium (Ge) and silicon (Si) have a ***repetitive crystal structure***, whereas compound semiconductors such as gallium arsenide (GaAs), cadmium sulfide (CdS), gallium nitride (GaN), and gallium arsenide phosphide (GaAsP) are constructed of ***two or more semiconductor materials of different atomic structures.***
- The three semiconductors used most frequently in the construction of electronic devices are ***Ge, Si, and GaAs.***

Semiconductor Materials: Ge, SI & GaAs Contd.

Germanium:

- **In the first few decades following the *discovery of the diode* in 1939 and *the transistor* in 1947 *germanium was used almost exclusively* because it was relatively easy to find and was available in fairly large quantities.**

- **It was also relatively *easy to refine to obtain very high levels of purity*, an important aspect in the fabrication process.**

- **However, it was discovered in the early years that diodes and transistors constructed using germanium as the base material *suffered from low levels of reliability due primarily to its sensitivity to changes in temperature.***

Semiconductor Materials: Ge, SI & GaAs Contd.

Silicon:

- At the time, scientists were aware that another material, ***silicon, had improved temperature sensitivities***, but the refining process for manufacturing silicon of very high levels of purity was still in the development stages.

- Finally, however, in 1954 the first silicon transistor was introduced, and silicon quickly became the semiconductor material of choice.

- Not only is silicon ***less temperature sensitive***, but it is one of the most ***abundant materials on earth***, removing any concerns about availability.

Gallium Arsenide:

- As time moved on, however, the field of electronics became increasingly sensitive to issues of speed.
- The result was the development of the first GaAs transistor in the early 1970s.
- This new transistor had ***speeds of operation up to five times that of Si***.
- GaAs was ***more difficult to manufacture at high levels of purity***, was ***more expensive***, and had little design support in the early years of development.
- However, in time ***the demand for increased speed*** resulted in more funding for GaAs research, to the point that today it is ***often used as the base material for new high-speed, very large scale integrated (VLSI) circuit designs***.

Covalent Bonding and Intrinsic Materials

- To fully appreciate why Si, Ge, and GaAs are the semiconductors of choice for the electronics industry requires some understanding of the atomic structure of each and how the atoms are bound together to form a crystalline structure.
- The fundamental components of an atom are the ***electron, proton, and neutron***.
- In the lattice structure, ***neutrons and protons form the nucleus*** and ***electrons appear in fixed orbits around the nucleus***. The Bohr model for the three materials is provided in Fig. 1.3.

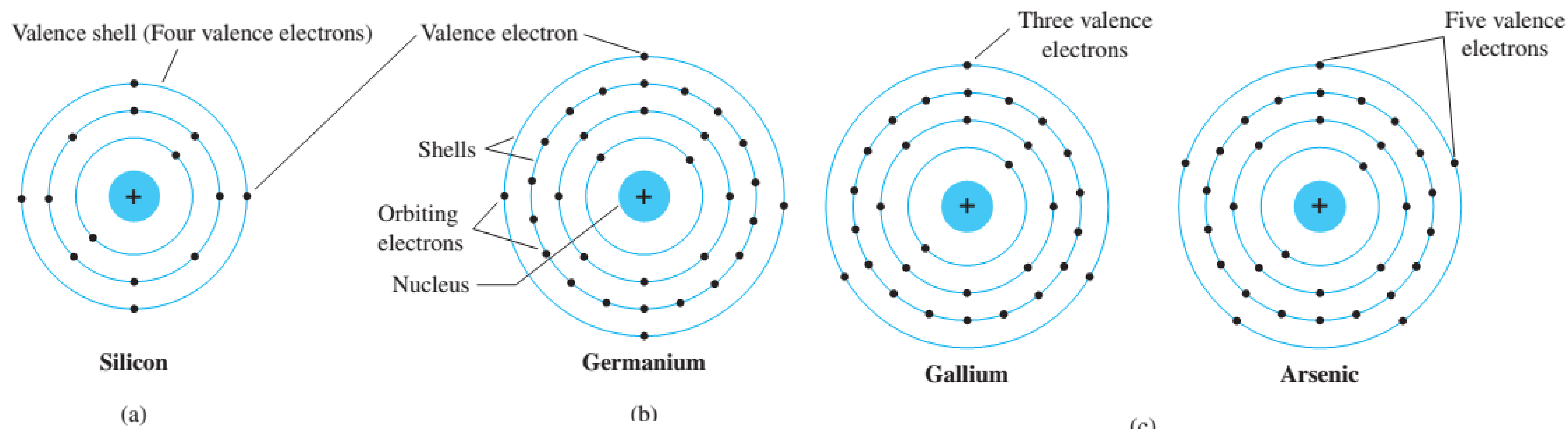


FIG. 1.3
Atomic structure of (a) silicon; (b) germanium; and (c) gallium and arsenic.

Covalent Bonding & Intrinsic Materials Contd.

- As indicated in Fig. 1.3, silicon has 14 orbiting electrons, germanium has 32 electrons, gallium has 31 electrons, and arsenic has 33 orbiting electrons (the same arsenic that is a very poisonous chemical agent).
- For germanium and silicon there are four electrons in the outermost shell, which are referred to as valence electrons.
- Gallium has three valence electrons and arsenic has five valence electrons.
- Atoms that have four valence electrons are called tetravalent , those with three are called trivalent, and those with five are called pentavalent.
- The term valence is used to indicate that the potential (ionization potential) required to remove any one of these electrons from the atomic structure is significantly lower than that required for any other electron in the structure.

Covalent Bonding & Intrinsic Materials Contd.

- **In a pure silicon or germanium crystal the four valence electrons of one atom form a bonding arrangement with four adjoining atoms, as shown in Fig. 1.4.**

- **This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding.**

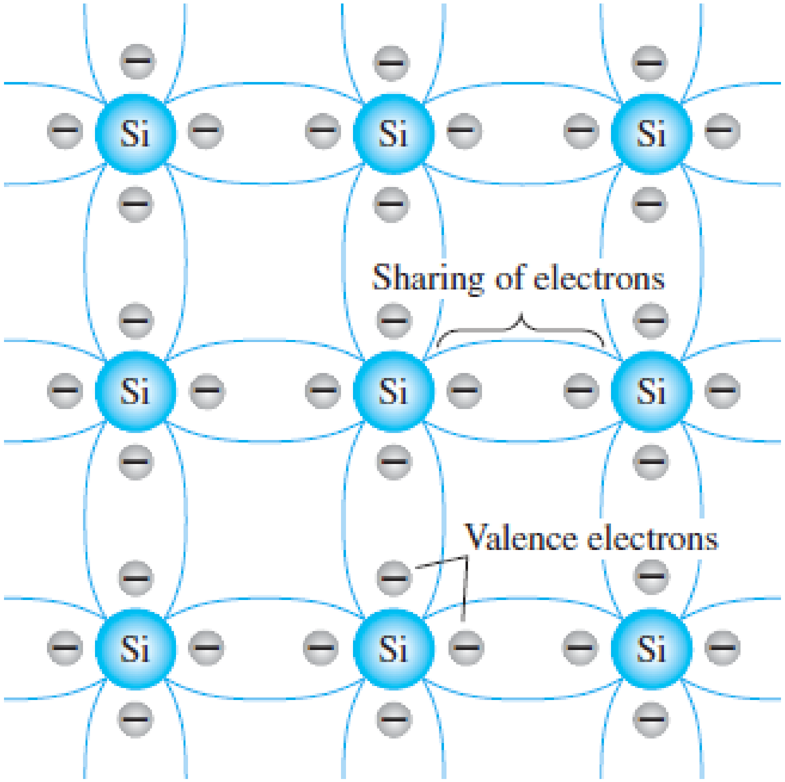


FIG. 1.4
Covalent bonding of the silicon atom.

Covalent Bonding & Intrinsic Materials Contd.

- ❖ Because GaAs is a compound semiconductor, there is sharing between the two different atoms, as shown in Fig. 1.5.

- ❖ Each atom, gallium or arsenic, is surrounded by atoms of the complementary type. There is still a sharing of electrons similar in structure to that of Ge and Si, but now five electrons are provided by the As atom and three by the Ga atom.

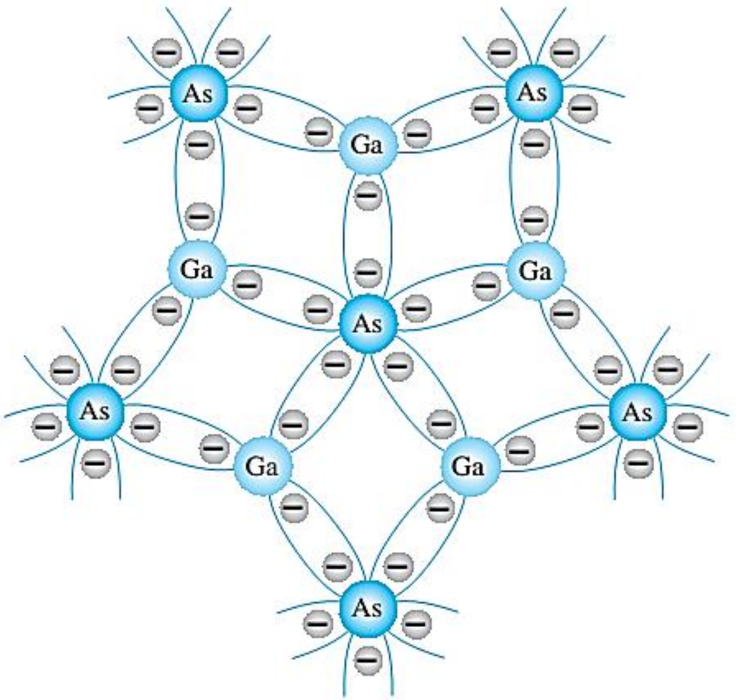


FIG. 1.5
Covalent bonding of the GaAs crystal.

Covalent Bonding & Intrinsic Materials Contd.

- Although the covalent bond will result in a stronger bond between the valence electrons and their parent atom, *it is still possible for the valence electrons to absorb sufficient kinetic energy* from external natural causes to *break the covalent bond and assume the "free" state.*
- *The term free is applied to any electron that has separated from the fixed lattice structure* and is *very sensitive to any applied electric fields* such as established by voltage sources or any difference in potential.
- The external causes include effects such as *light energy in the form of photons* and *thermal energy (heat) from the surrounding medium*.
- At room temperature there are approximately 1.5 * 10^{10} free carriers in 1 cm3 of intrinsic silicon material, that is, 15,000,000,000 (15 billion) electrons in a space smaller than a small sugar cube - an enormous number.

Covalent Bonding & Intrinsic Materials Contd.

- ***The term intrinsic is applied*** to any semiconductor material that has been carefully ***refined to reduce the number of impurities to a very low level***-essentially as pure as can be made available through modern technology.
- The free electrons in a material due only to external causes are referred to as intrinsic carriers. Table1.1 compares the number of intrinsic carriers per cubic centimeter(abbreviated n_i) for Ge, Si, and GaAs.

TABLE 1.1
Intrinsic Carriers n_i

Semiconductor	Intrinsic Carriers (per cubic centimeter)
GaAs	1.7×10^{6}
Si	1.5×10^{10}
Ge	2.5×10^{13}

TABLE 1.2
Relative Mobility Factor μ_n

Semiconductor	μ_n (cm^2/V·s)
Si	1500
Ge	3900
GaAs	8500

Covalent Bonding & Intrinsic Materials Contd.

- **It is interesting to note that Ge has the highest number and GaAs the lowest.**
- **In fact, Ge has more than twice the number as GaAs.**
- **The number of carriers in the intrinsic form is important, but other characteristics of the material are more significant in determining its use in the field.**
- **One such factor is *the relative mobility (μ_n)* of the free carriers in the material, that is, *the ability of the free carriers to move throughout the material*.**
- **Table 1.2 clearly reveals that the free carriers in GaAs have *more than five times the mobility* of free carriers in Si, a factor that results in response times using GaAs electronic devices that can be up to five times those of the same devices made from Si.**
- **Note also that free carriers in Ge have *more than twice the mobility of electrons* in Si, a factor that results in the continued use of Ge in high-speed radio frequency applications.**

Covalent Bonding & Intrinsic Materials Contd.

- **Extremely high levels of purity are necessary because the addition of one part of impurity (of the proper type) per million in a wafer of silicon material can *change that material from a relatively poor conductor to a good conductor of electricity*.**

- ***The ability to change the characteristics of a material through this process is called doping*, something that germanium, silicon, and gallium arsenide readily and easily accept.**

- **One important and interesting *difference between semiconductors and conductors* is their reaction to *the application of heat*.**

Covalent Bonding & Intrinsic Materials Contd.

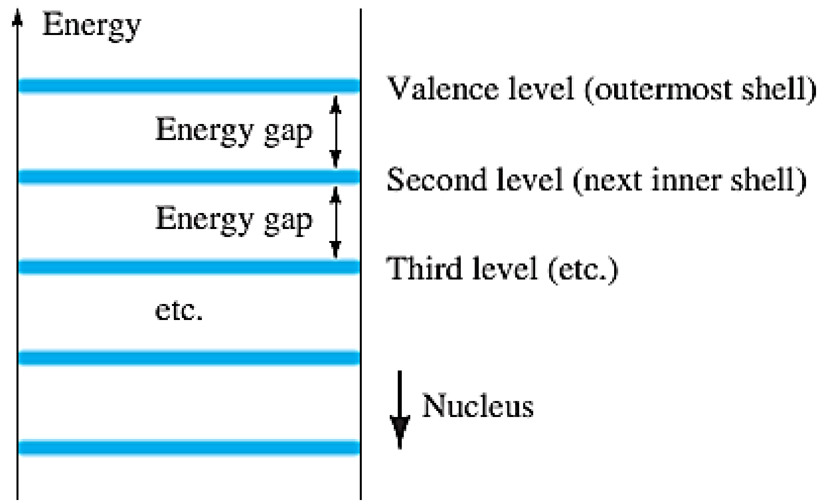
- **For conductors, the resistance increases with an increase in heat. This is because the numbers of carriers in a conductor do not increase significantly with temperature, but their vibration pattern about a relatively fixed location makes it increasingly difficult for a sustained flow of carriers through the material.**
- **Materials that react in this manner are said to have a *positive temperature coefficient*.**
- **Semiconductor materials, however, exhibit an *increased level of conductivity with the application of heat*. As the temperature rises, an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and to contribute to the number of free carriers.**
- **Semiconductor materials have a *negative temperature coefficient*.**

Energy Levels

- Within the atomic structure of each and every isolated atom there are specific energy levels associated with each shell and orbiting electron, as shown in Fig. 1.6.

- The energy levels associated with each shell will be different for every element.

- The farther an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.



(a)

Energy Levels Contd.

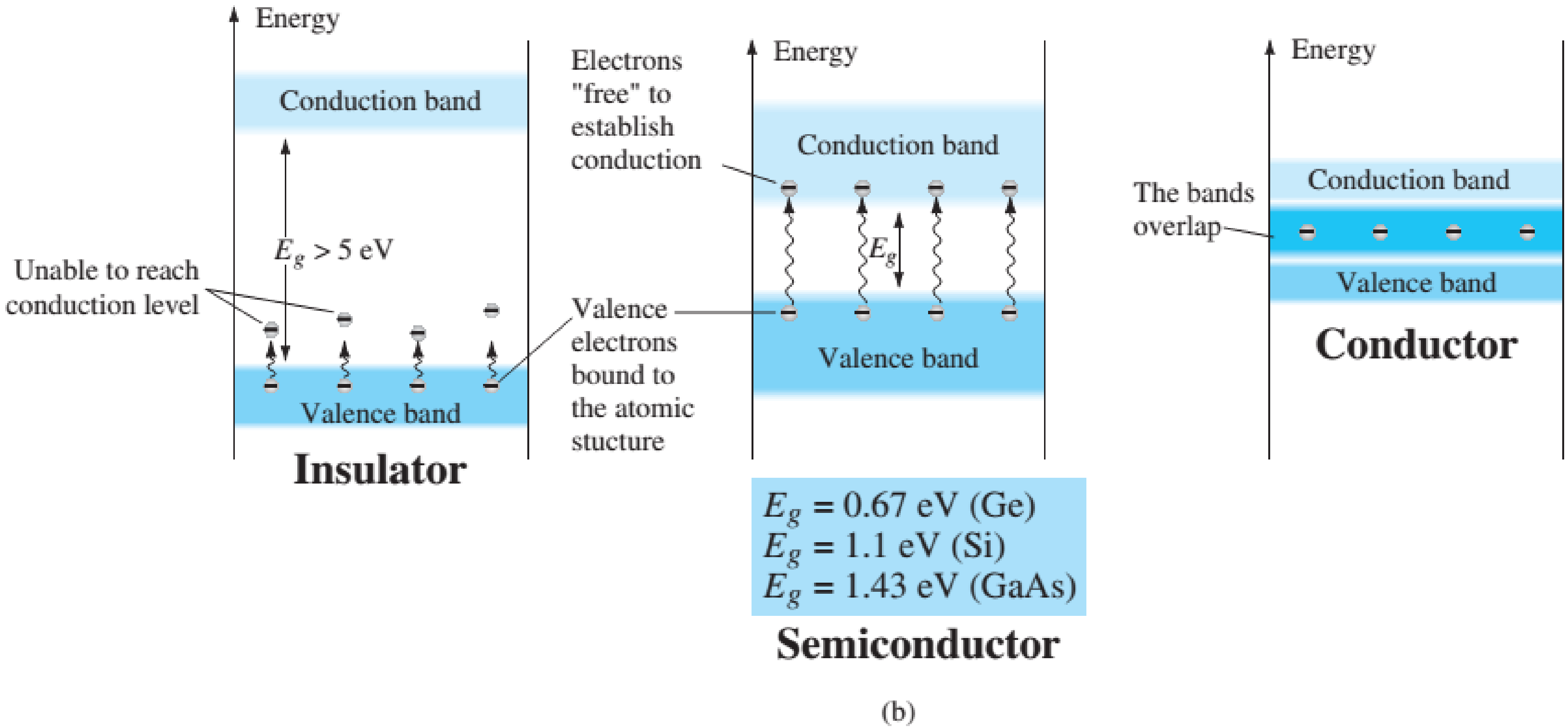


FIG. 1.6

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

n-Type & p-Type Materials

- The ***characteristics of a semiconductor material can be altered*** significantly by the ***addition of specific impurity atoms*** to the relatively pure semiconductor material.

- These impurities, although only ***added at 1 part in 10 million***, can ***alter the band structure sufficiently*** to totally change the electrical properties of the material.

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

- There are two extrinsic materials of immeasurable importance to semiconductor device fabrication: ***n -type and p -type materials***.

n-Type Material

- Both n -type and p -type materials are formed by ***adding a predetermined number of impurity atoms*** to a silicon base.

- An n -type material is created by introducing impurity elements that have **five valence electrons (pentavalent),** such as antimony, arsenic, and phosphorus. (Group V elements in Periodic Table)

- The effect of such impurity elements is indicated in Fig. 1.7 (using antimony as the impurity in a silicon base).

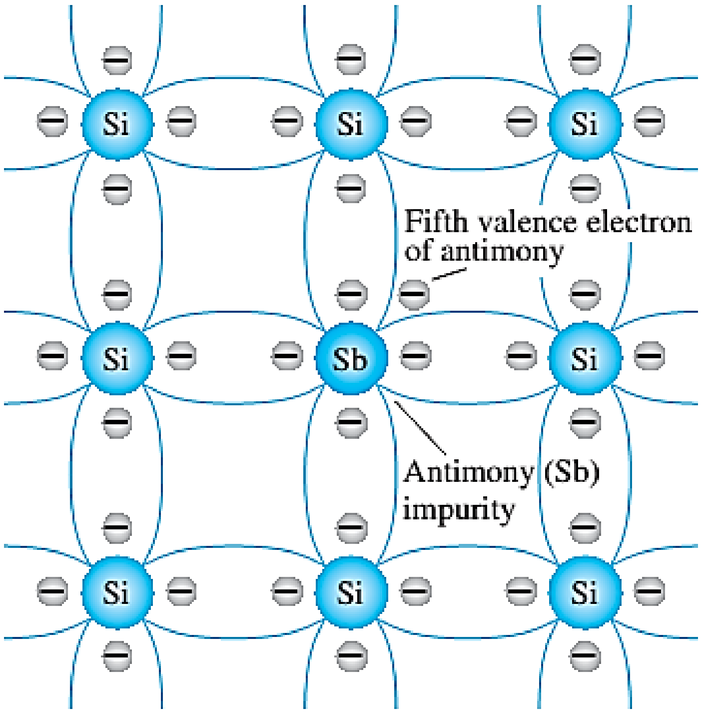


FIG. 1.7
Antimony impurity in n-type material.

n-Type Material Contd.

- **Note that the four covalent bonds are still present. There is, however, *an additional fifth electron due to the impurity atom*, which is unassociated with any particular covalent bond.**

- **This remaining electron, loosely bound to its parent (antimony) atom, is relatively free to move within the newly formed n -type material.**

- **Diffused impurities with five valence electrons are called *donor atoms.***

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

n-Type Material Contd.

- Those ***free electrons due to the added impurity sit at this energy level*** and have less difficulty absorbing a sufficient measure of thermal energy to move into the conduction band at room temperature.

- The result is that at room temperature, there are a large number of carriers (electrons) in the conduction level, and the conductivity of the material increases significantly.

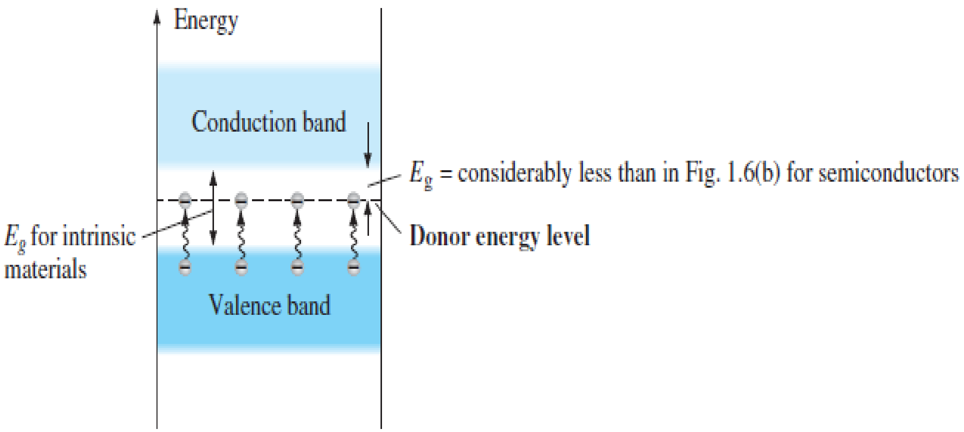


FIG. 1.8
Effect of donor impurities on the energy band structure.

p-Type Material

- The p -type material is formed by ***doping a pure germanium or silicon crystal with impurity atoms having three valence electrons***.

- **The elements most frequently used for this purpose are boron, gallium, and indium. (Group III elements in Periodic Table)**

- **Note that there is now *an insufficient number of electrons to complete the covalent bonds* of the newly formed lattice.**

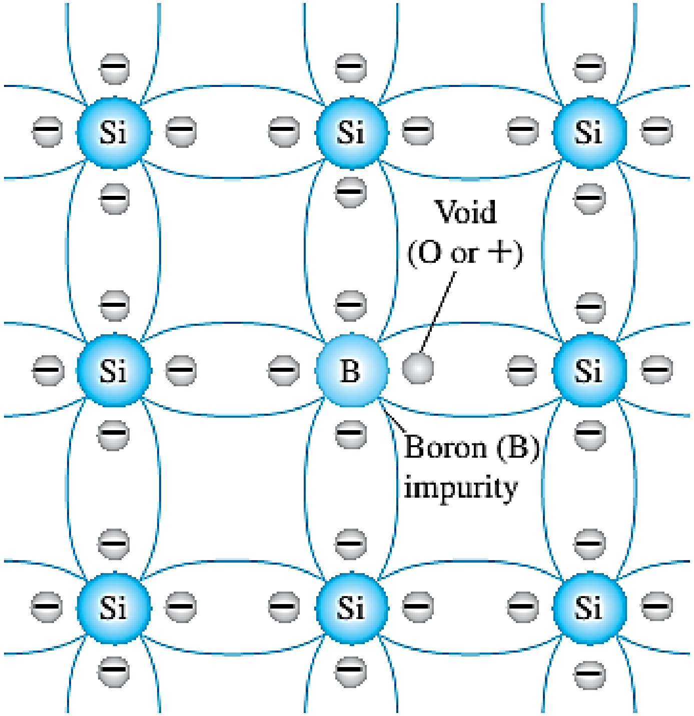


FIG. 1.9
Boron impurity in p-type material.

p-Type Material Contd.

- **The resulting vacancy is called a hole and is represented by a small circle or a plus sign, indicating the absence of a negative charge.**

- **Since the resulting vacancy will readily accept a free electron:**

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

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

Electron vs Hole Flow

The effect of the hole on conduction is shown in Fig. 1.10 . If a valence electron *<u>acquires sufficient kinetic energy to break its covalent bond</u>* and *<u>fills the void created by a hole</u>*, then a vacancy, or hole, will be created in the covalent bond that released the electron.

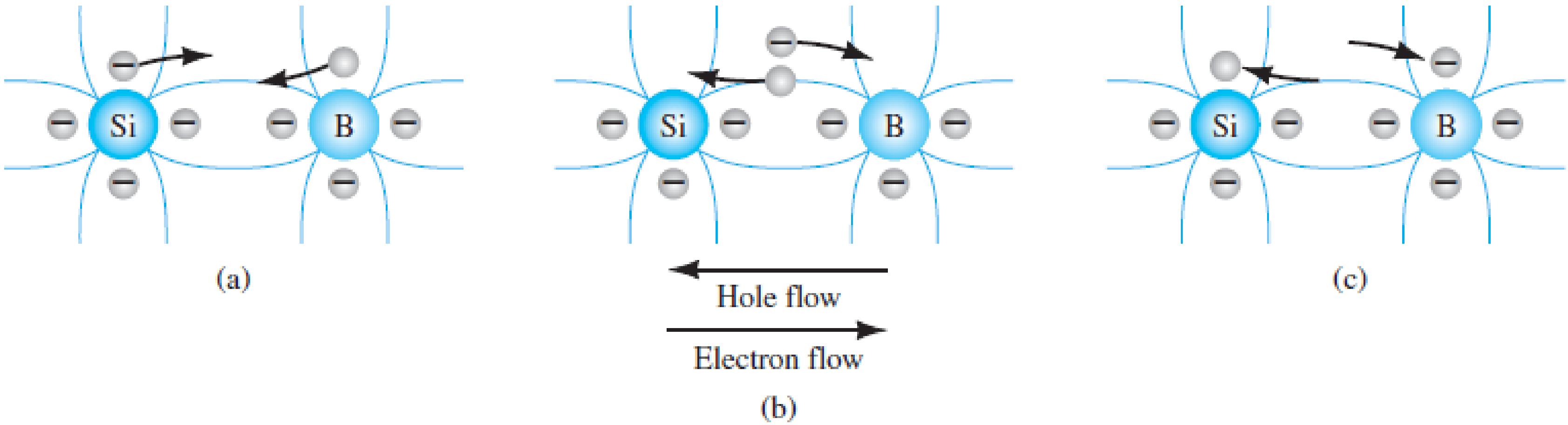


FIG. 1.10
Electron versus hole flow.

Majority & Minority Carriers

- In an n-type material (Fig. 1.11a) the electron is called the majority carrier and the hole the minority carrier.
- In a p-type material the hole is the majority carrier and the electron is the minority carrier.

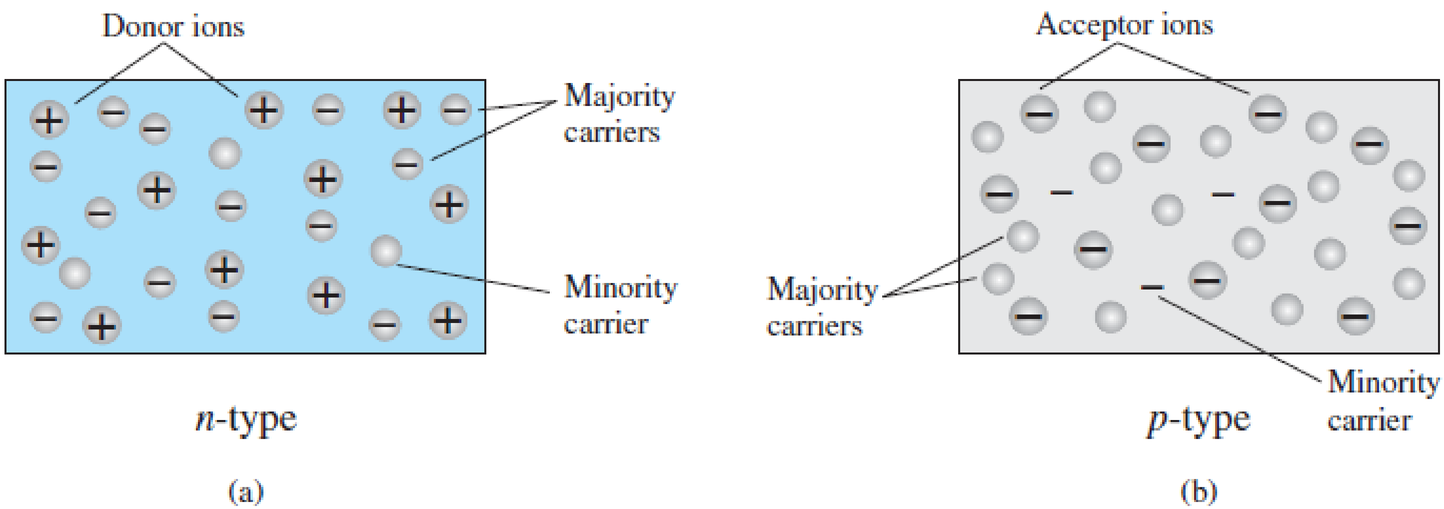


FIG. 1.11
(a) n-type material; (b) p-type material.

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)

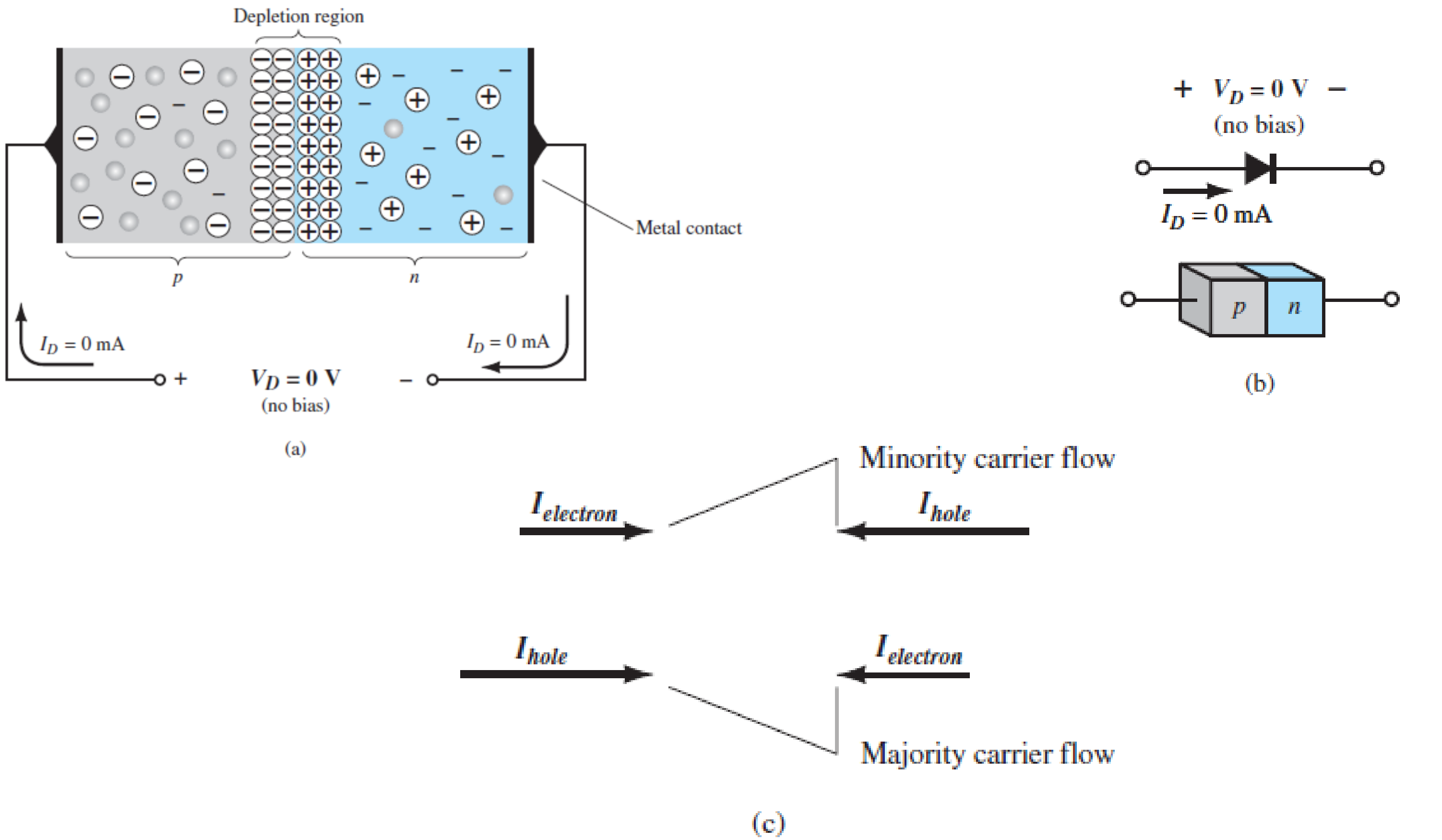


FIG. 1.12

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 .

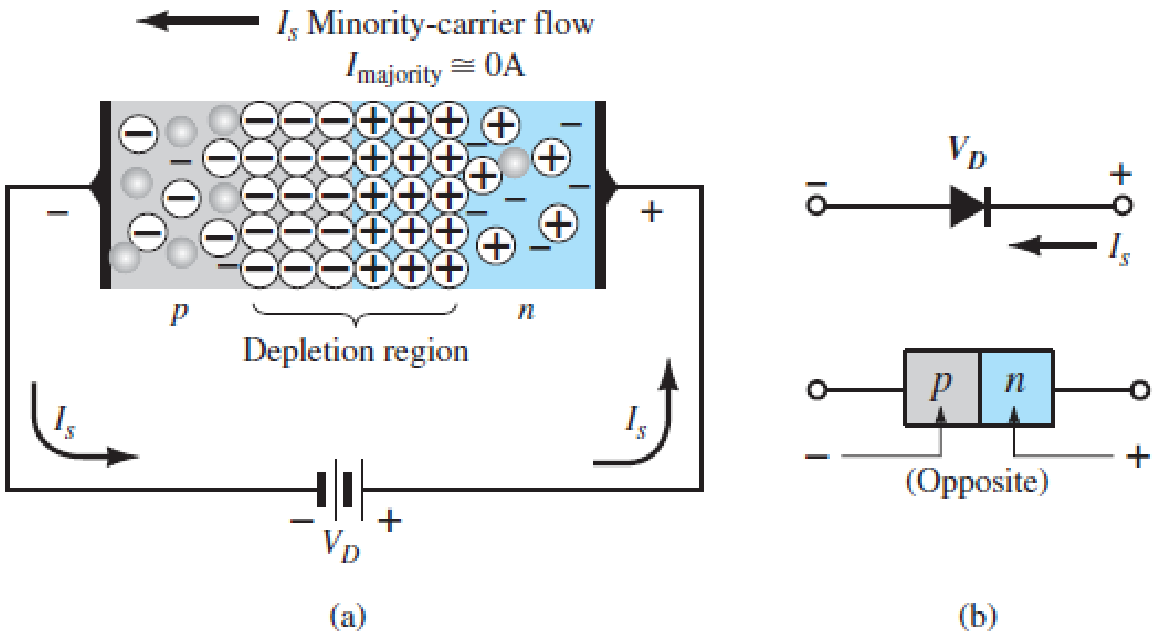


FIG. 1.13

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 .

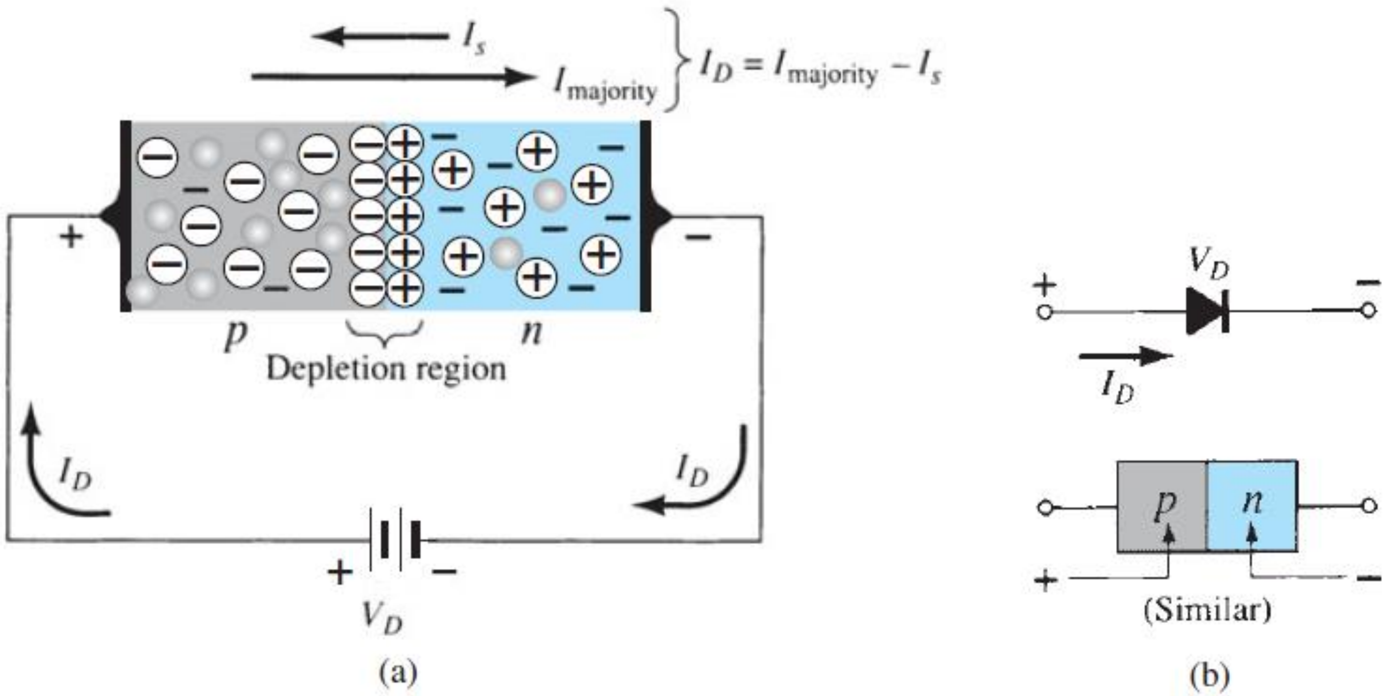


FIG. 1.14

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

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

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

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

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

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

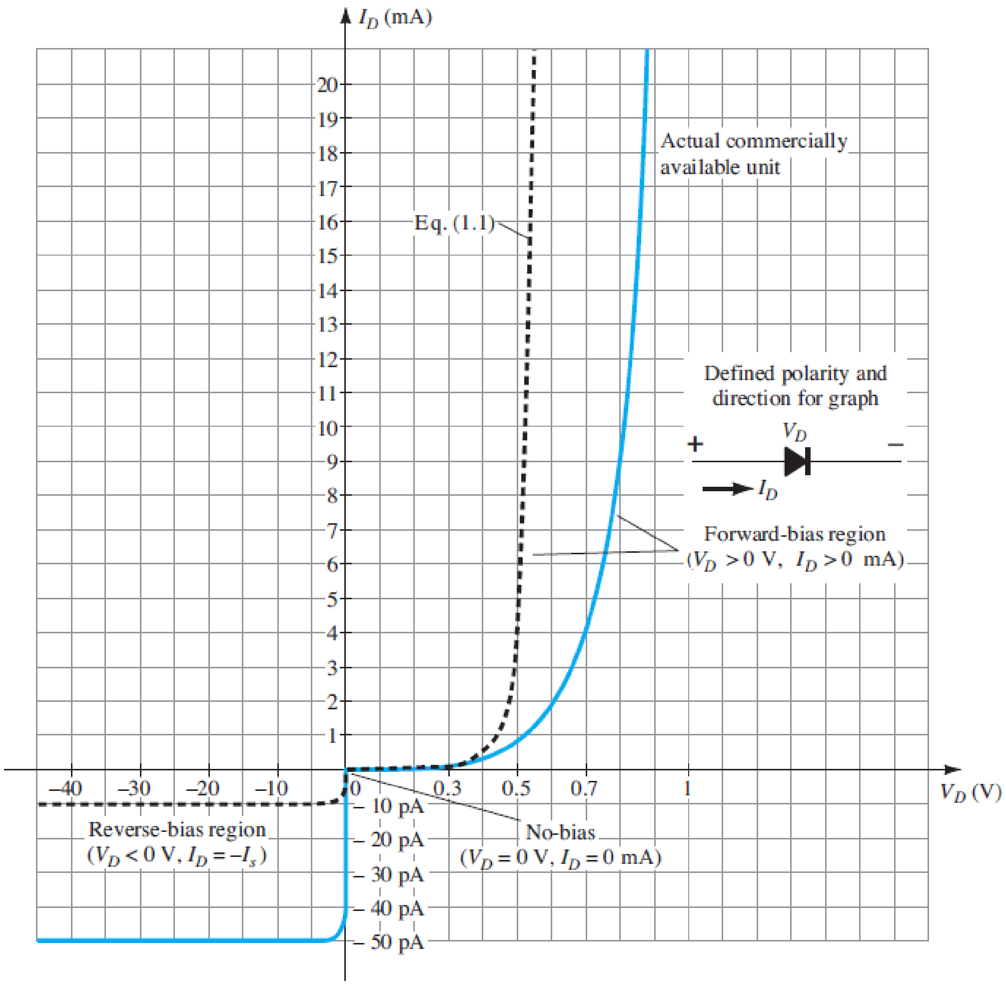


FIG. 1.15

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.

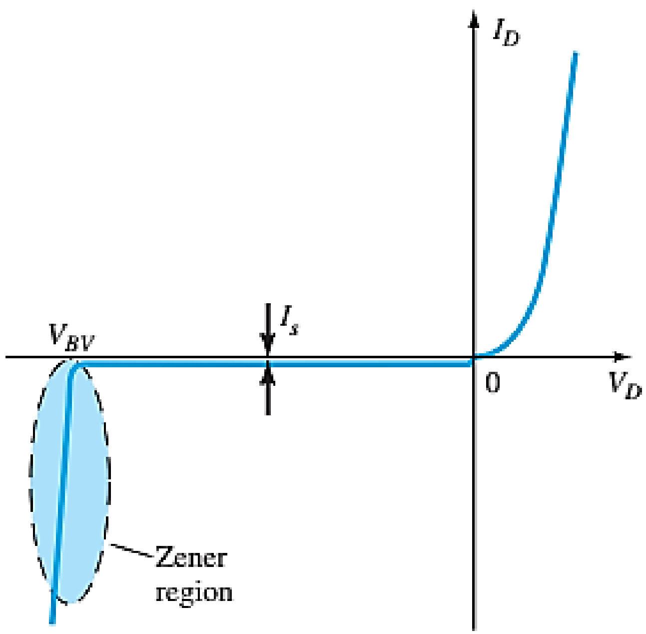


FIG. 1.17
Breakdown region.

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 Is 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

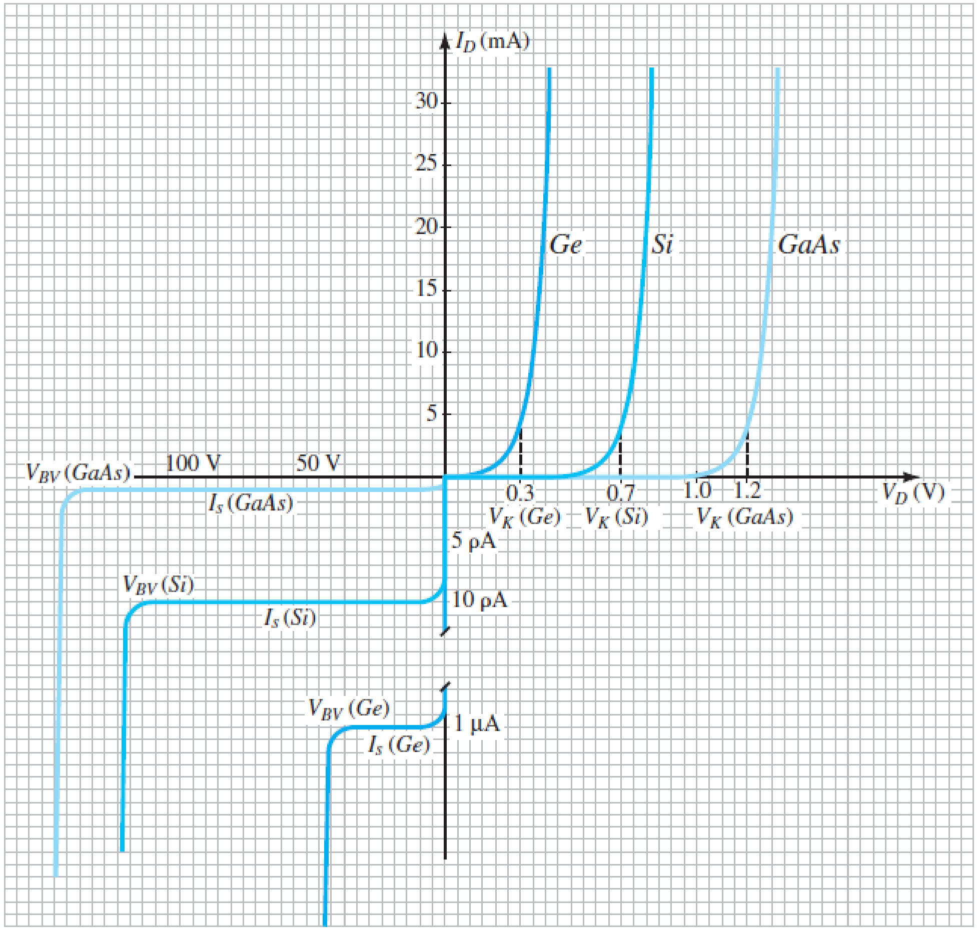


FIG. 1.18
Comparison of Ge, Si, and GaAs commercial diodes.

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.

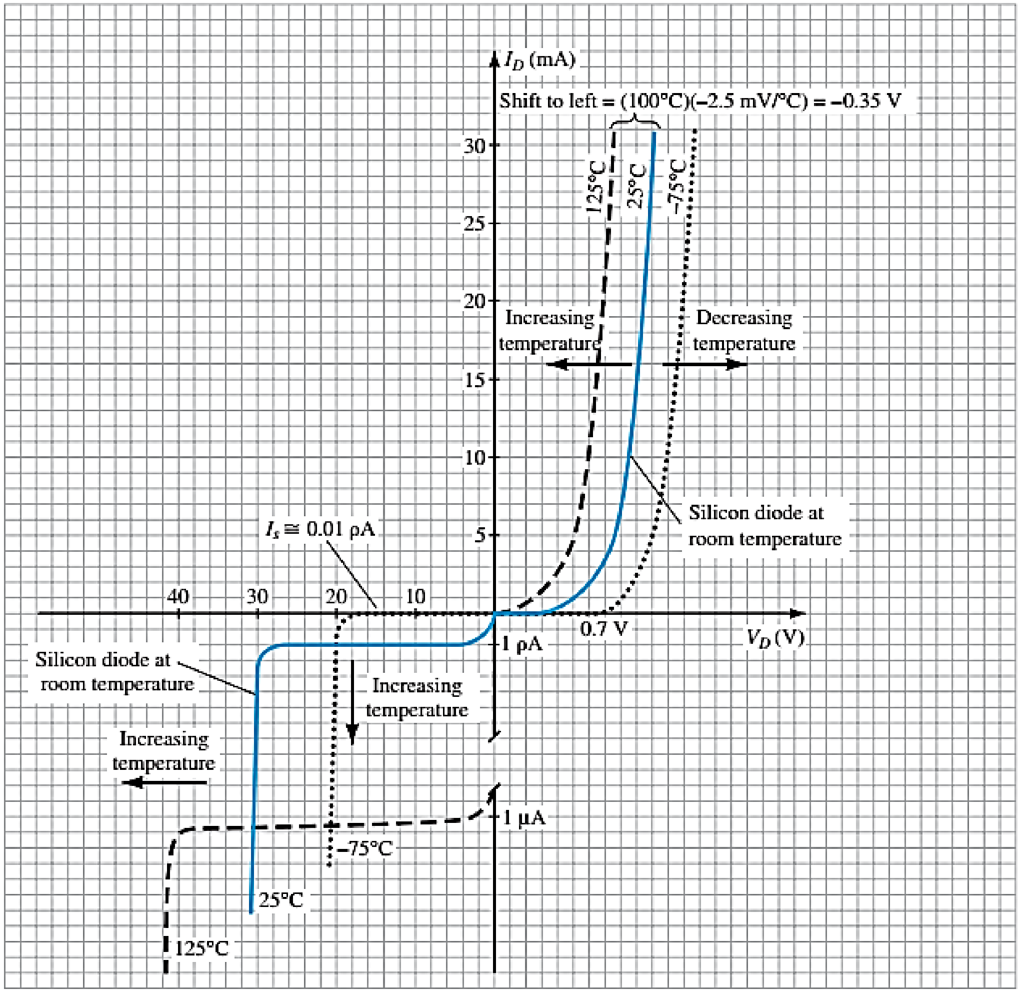


FIG. 1.19
Variation in Si diode characteristics with temperature change.

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.

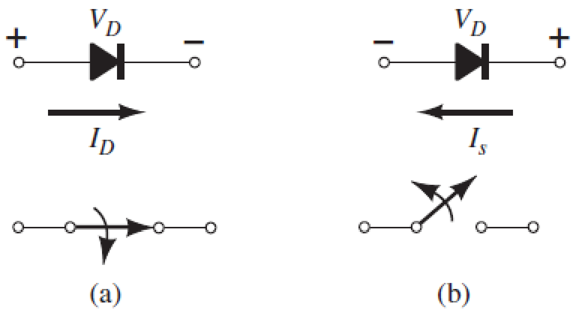


FIG. 1.21
Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

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.

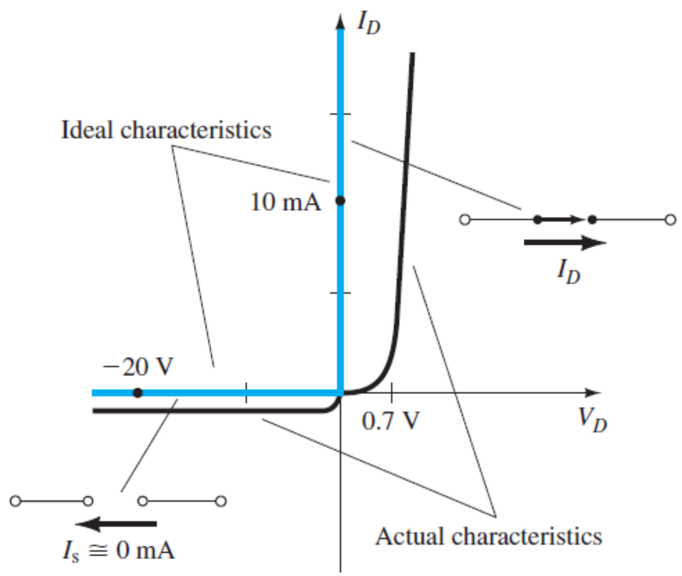


FIG. 1.22
Ideal versus actual semiconductor characteristics.

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*.**

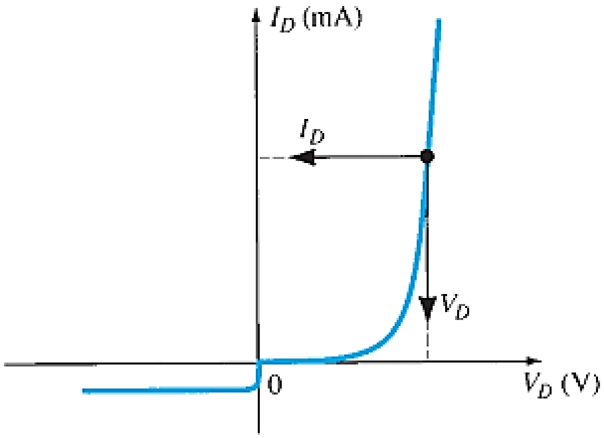


FIG. 1.23
Determining the dc resistance of a diode at a particular operating point.

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)

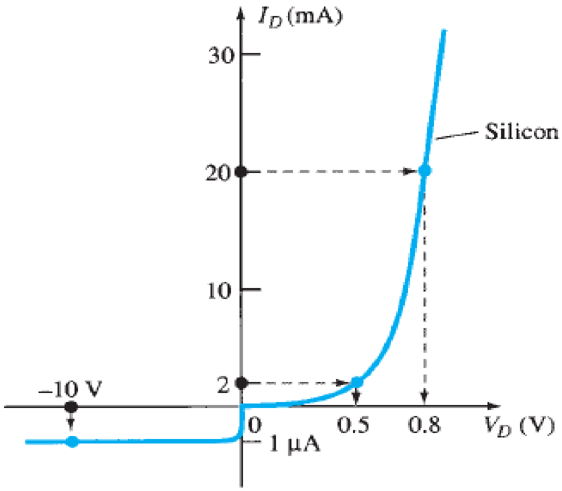


FIG. 1.24
Example 1.3.

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.***

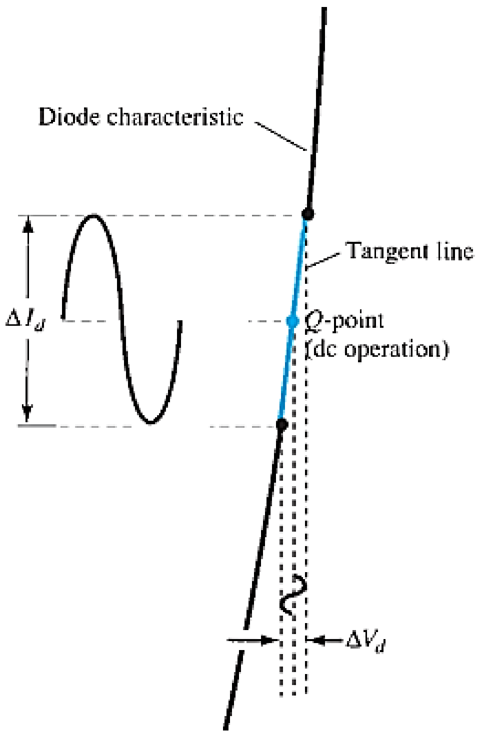


FIG. 1.25
Defining the dynamic or ac resistance.

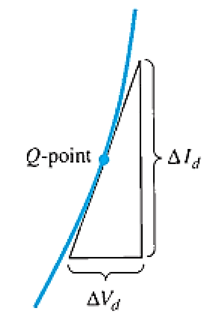


FIG. 1.26
Determining the ac resistance at a Q-point.

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.**

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

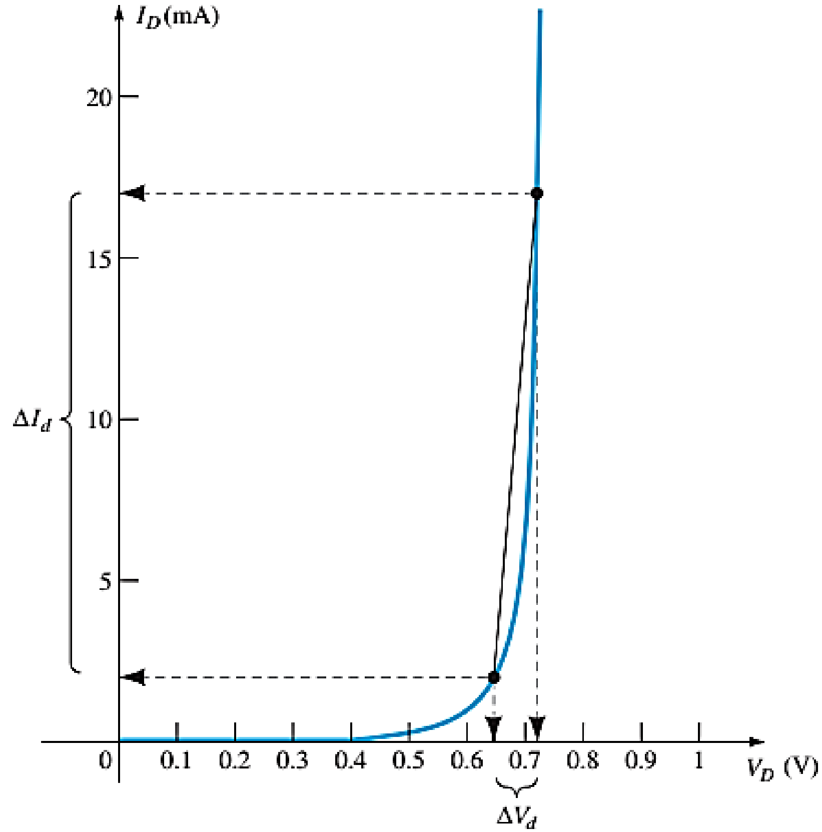
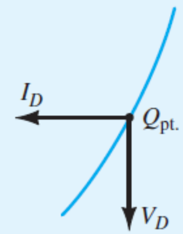
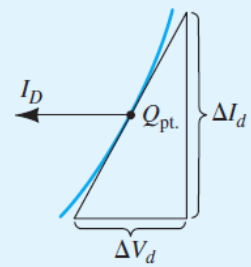
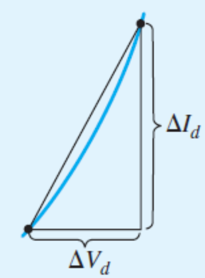


FIG. 1.28
Determining the average ac resistance between indicated limits.

Summary table

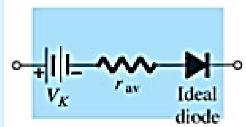
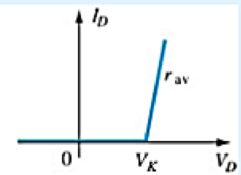
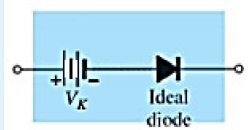
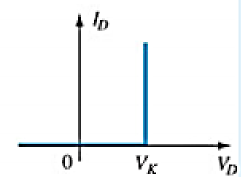
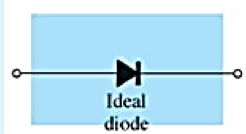
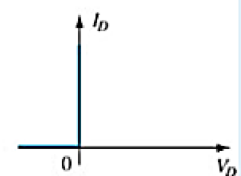
TABLE 1.6
Resistance Levels

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	$r_{av} = \left.\dfrac{\Delta V_d}{\Delta I_d}\right\|_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

Diode Equivalent Circuits

An equivalent circuit is a <u>*combination of elements properly chosen to best represent the actual terminal characteristics of a device or system*</u> 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	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

Reverse Recovery Time

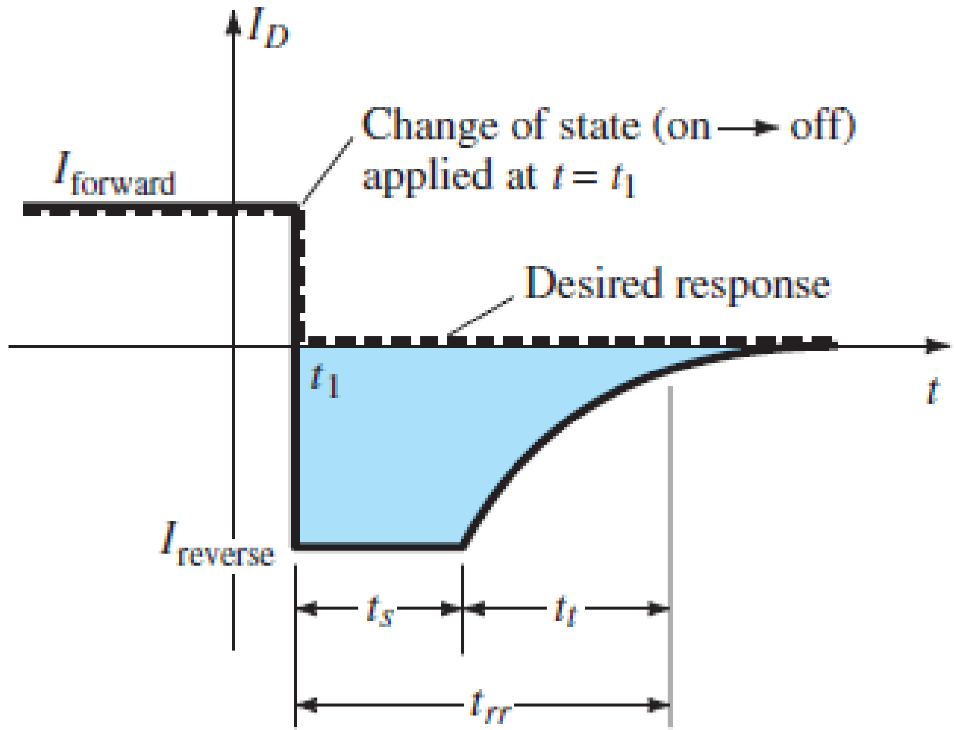


FIG. 1.35

Defining the reverse recovery time.

Reverse Recovery Time Contd.

- There are certain pieces of data that are normally provided on diode specification sheets provided by manufacturers. One such quantity that has not been considered yet is the reverse recovery time, denoted by t_{rr}.
- In the forward-bias state it was shown earlier that there are a large number of electrons from the *n*-type material progressing through the *p*-type material and a large number of holes in the *n*-type material—a requirement for conduction. The electrons in the *p*-type material and holes progressing through the *n*–type material establish a large number of minority carriers in each material.
- If the applied voltage should be reversed to establish a reverse-bias situation, we would ideally like to see the diode change instantaneously from the conduction state to the nonconduction state. However, because of the large number of minority carriers in each material, the diode current will simply reverse as shown in Fig. 1.35 and stay at this measurable level for the period of time t_s (storage time) required for the minority carriers to return to their majority-carrier state in the opposite material. In essence, the diode will remain in the short-circuit state with a current $I_{reverse}$ determined by the network parameters.

END of Chapter 1