Semiconductor Diodes

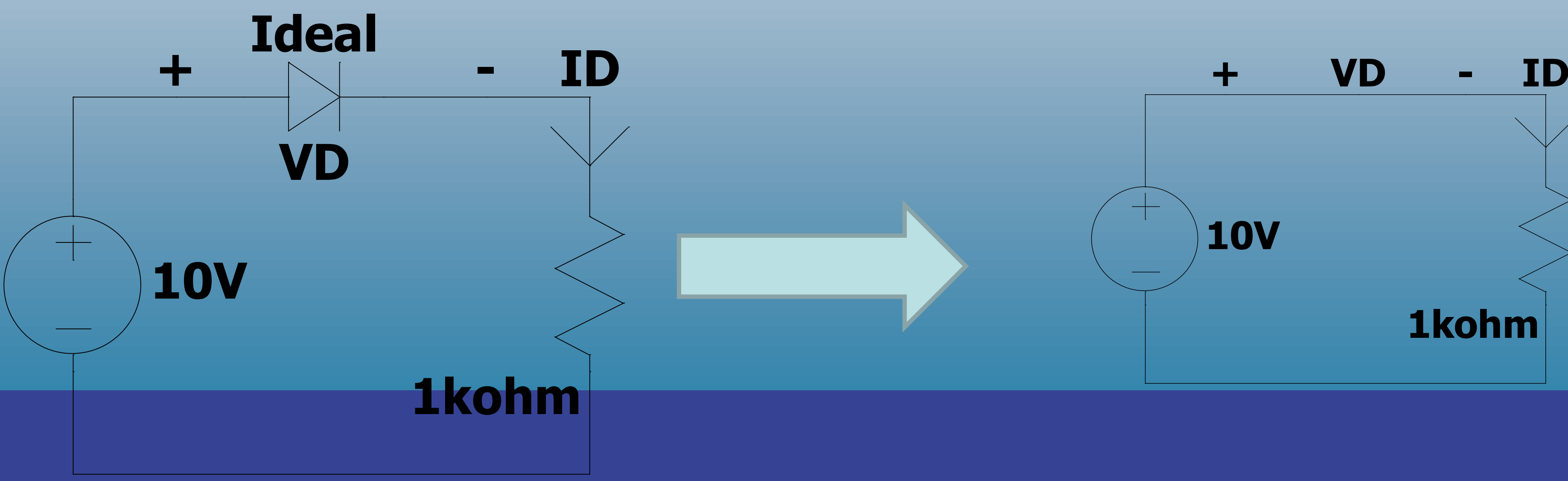
Topic 1 (Chapter 1)

A simple Diode circuit

- Forward Bias (FB)/Short/Conduction Mode: Positive terminal of diode connected with positive terminal of source.

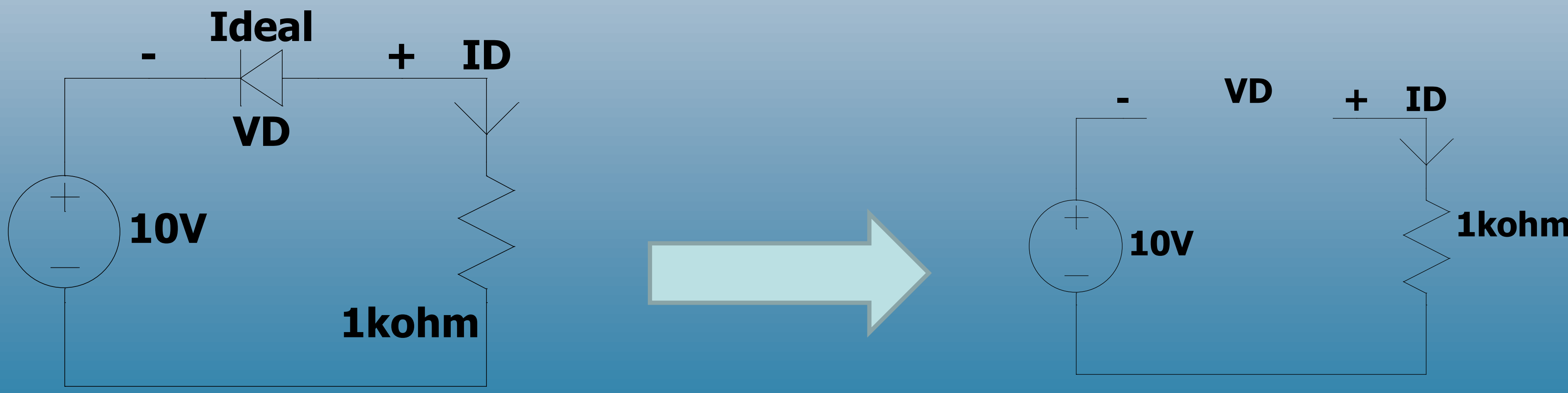
- Diode like short circuit.

- $V_D = V_{short} = 0V. I_D \neq 0 = \frac{10}{1k} = 10mA$



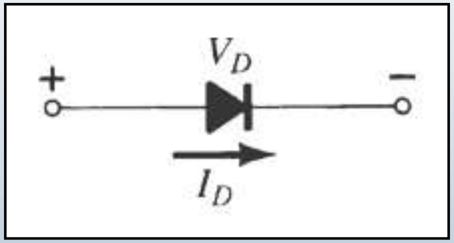
A simple Diode circuit

- Reverse Bias (RB)/Open/Non-conduction Mode: Positive terminal of diode connected with negative terminal of source.
- Diode like open circuit.
- $I_D = I_{open} = 0A. V_D \neq 0 = -10V$

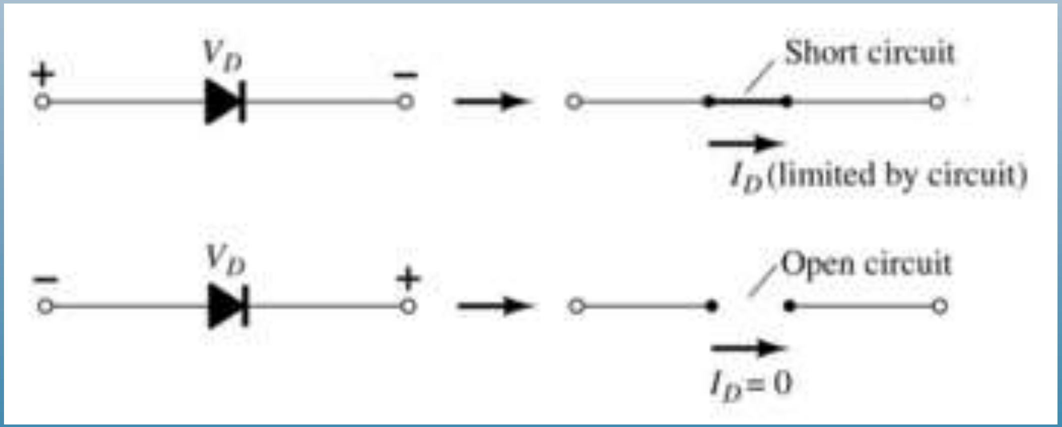


Diodes

The diode is a 2-terminal device.

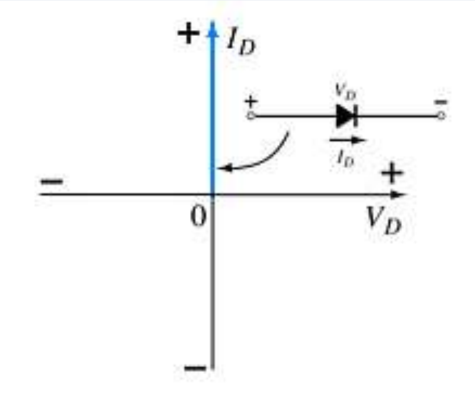


A diode ideally conducts in only one direction.



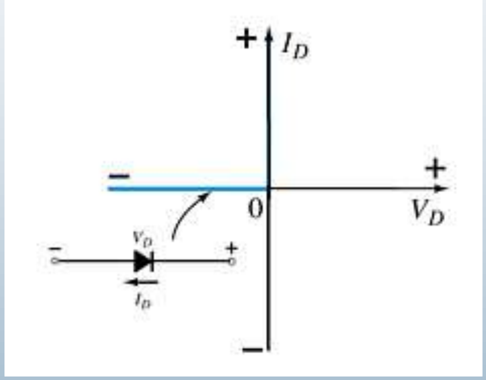
Diode Characteristics

Conduction Region



- The voltage across the diode is 0 V
- The diode acts like a short

Non-Conduction Region



- All of the voltage is across the diode
- The current is 0 A
- The diode acts like open

1.2 Semiconductor Materials

Materials commonly used in the development of semiconductor devices:

Silicon (Si)

Germanium (Ge)

Gallium Arsenide (GaAs)

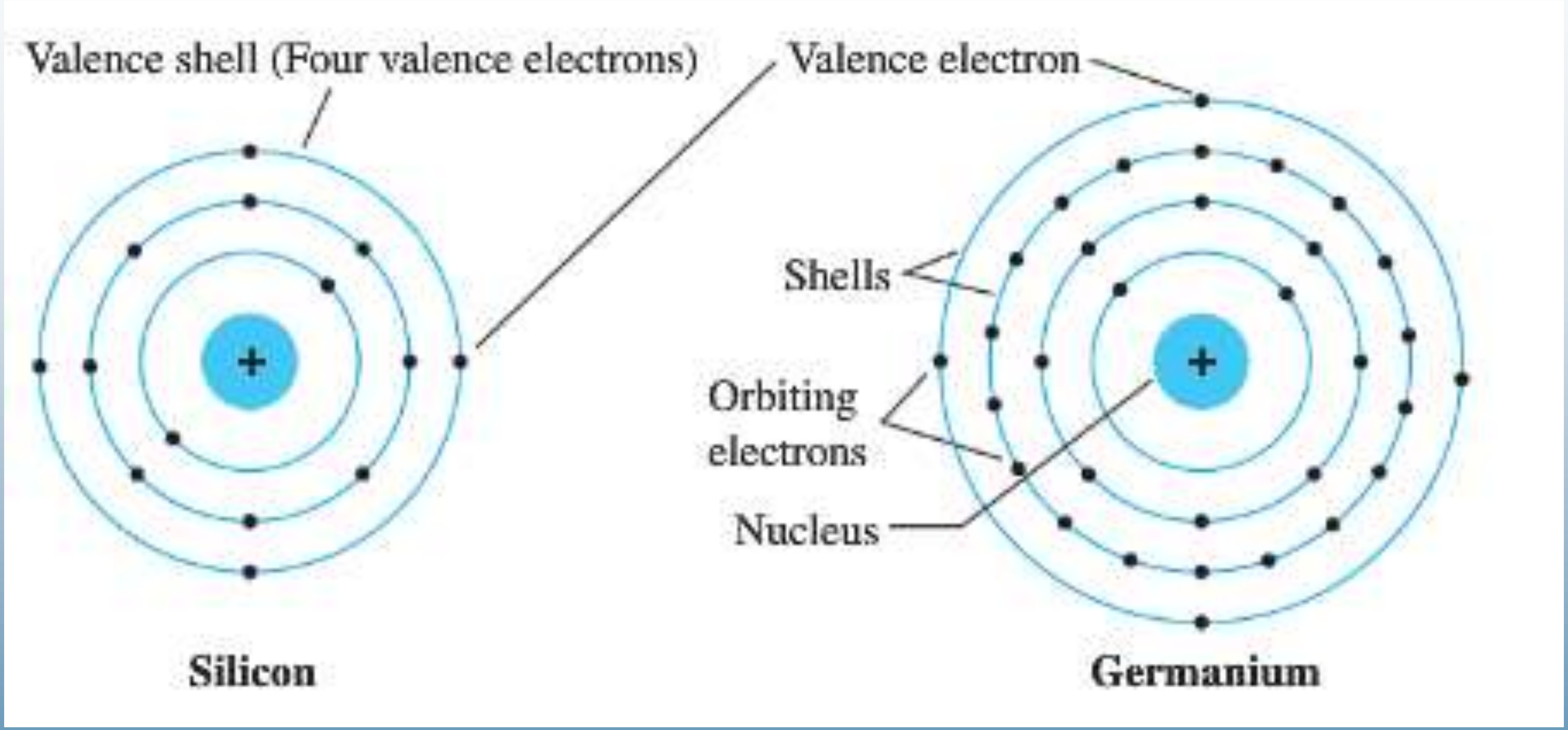
What are Semiconductors?

- Semiconductors are a group of materials having electrical conductivities intermediate between metals (conductors) and insulators.
- Their conductivities can be varied by changes in:
  - temperature,
  - impurity content.

History of Popular Semiconductors

- **Ge (Germanium)** was widely used in the early days.
- **Si (Silicon)** is now used for the majority of integrated circuits (ICs).
- The compound semiconductors are widely used in high-speed devices and opto-electronic devices
  - For example, **III–V semiconductors** such as GaN, GaP, and GaAs are common in light- emitting diodes (LEDs)
- **Three-element or ternary** semiconductors (such as GaAsP) and **four-element or quaternary** semiconductors (such as InGaAsP) are also used.
  - For example, they can be used to make LEDs of different colors.

1.3 Atomic Structures of Semiconductors

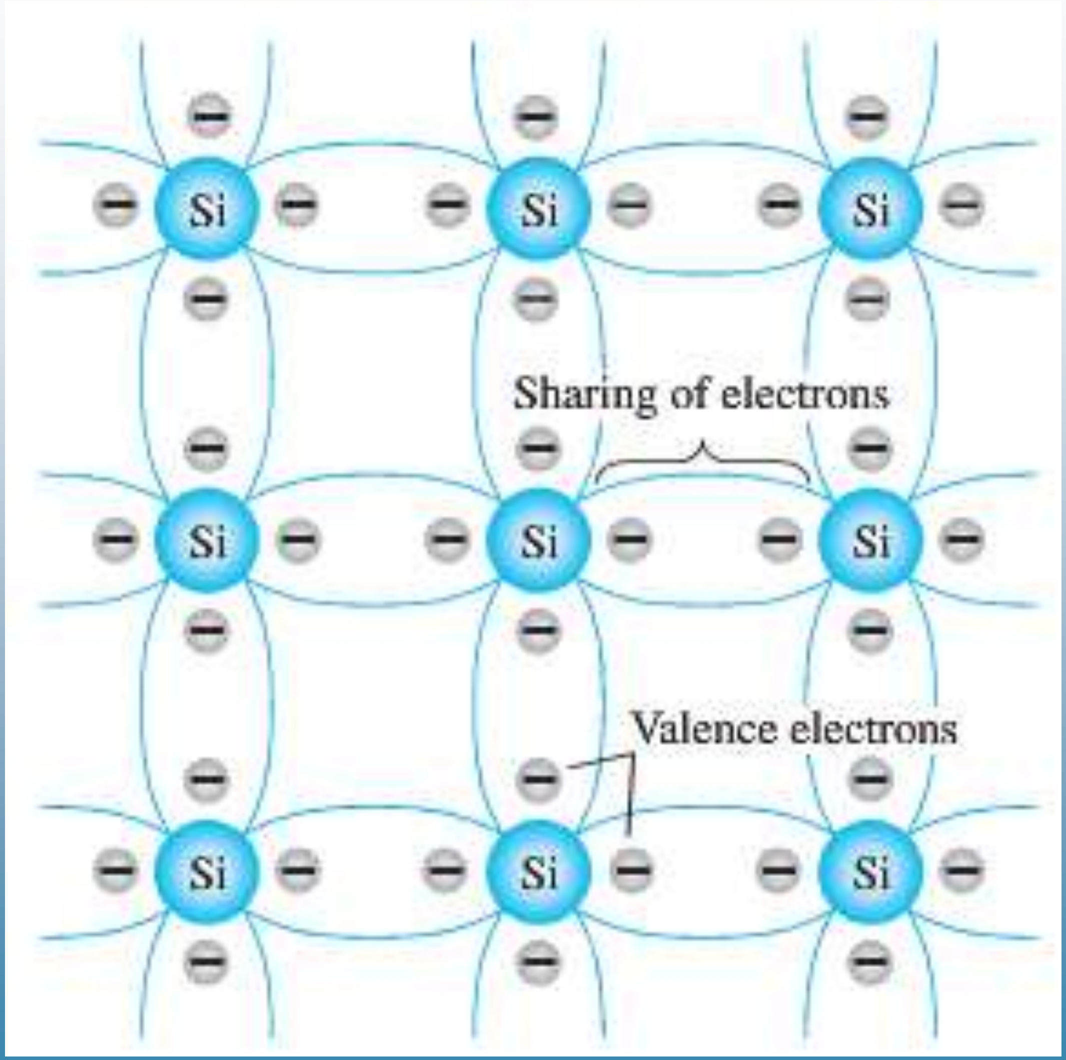


Valence electrons: Electrons in the outermost shell of an atom.

Si and Ge are Tetravalent atoms with four valence electrons

$$Z_{Si} = 14 \qquad Z_{Ge} = 32$$

Covalent bonding of the silicon atom



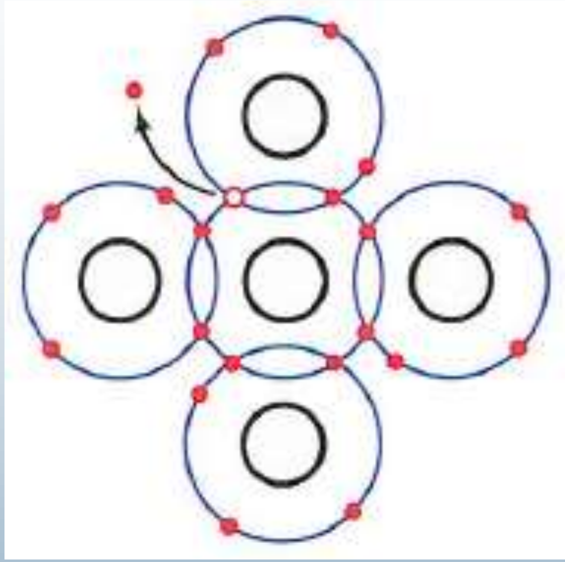
Intrinsic Semiconductors

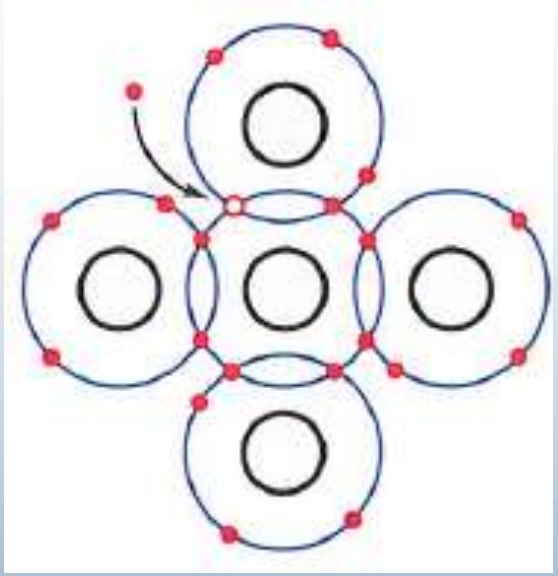
- Semiconductor materials two types:

1. Intrinsic Semiconductors
2. Extrinsic Semiconductors

- A pure semiconductor
- Carefully refined to reduce the number of impurities to a very low level
- Intrinsic carriers: free electrons in a material due only to external causes (energy from light or heat)

Electron Hole Pair Generation and Recombination





- Valence electrons can absorb sufficient energy (from light or heat) to break the covalent bonds and assume the “free” state.
  - These free electrons are called **intrinsic carriers**
- Higher temperatures creates more intrinsic carriers – hence higher conductivity

1.5 n-TYPE AND p-TYPE MATERIALS

- The electrical properties of a semiconductor can be altered significantly by adding impurity atoms
  - This process is called **doping**
  - A **doped** semiconductor is called **extrinsic**
- **There are just two types of extrinsic semiconductor materials:**

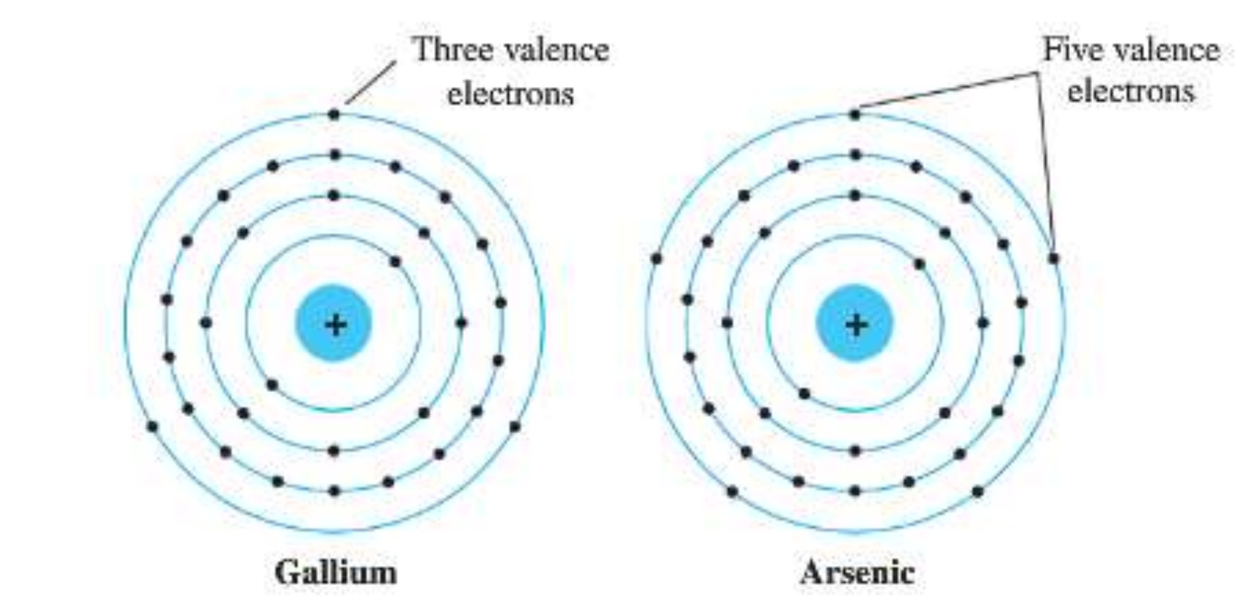
***n*-type**

***p*-type**

***n*-type** materials contain an excess of conduction band electrons.

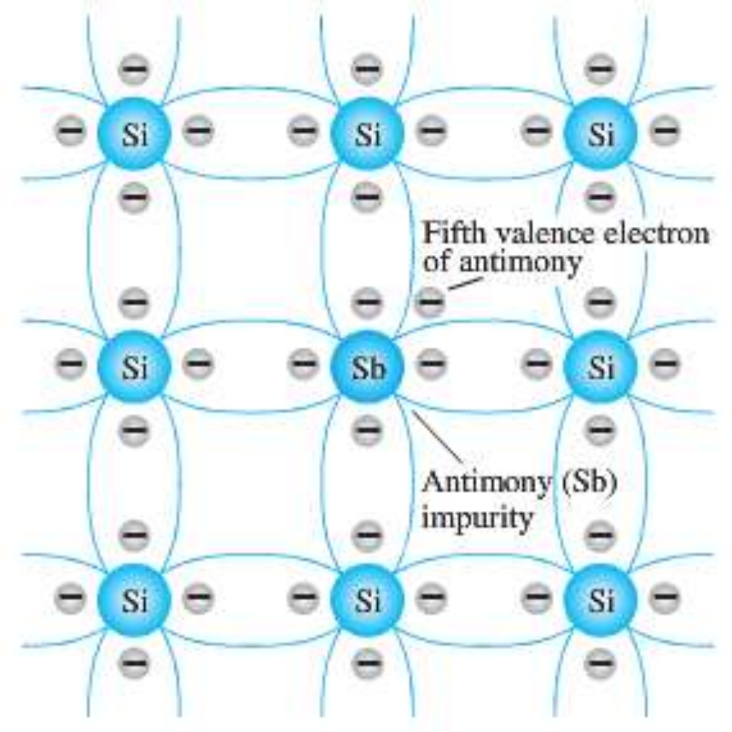
***p*-type** materials contain an excess of valence band holes.

Atomic Structures of Impurities



- p-type material is created by adding trivalent impurity elements such as B, Ga, and In
- n-type material is created by adding pentavalent impurity elements such as Sb, As, and P

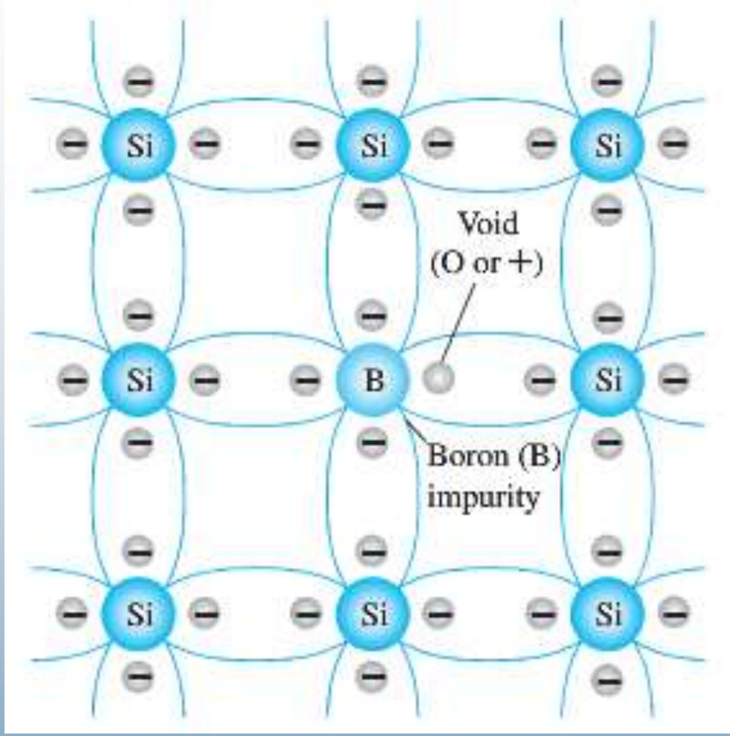
n -Type Material



Antimony impurity in n-type material.

- Impurities with five valence electrons (pentavalent) are called **donor** atoms, because the inserted impurity atom has donated a relatively “free” electron to the structure

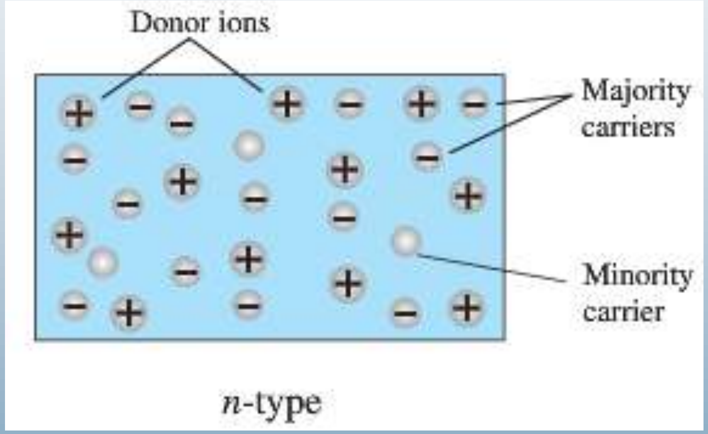
p-Type Material

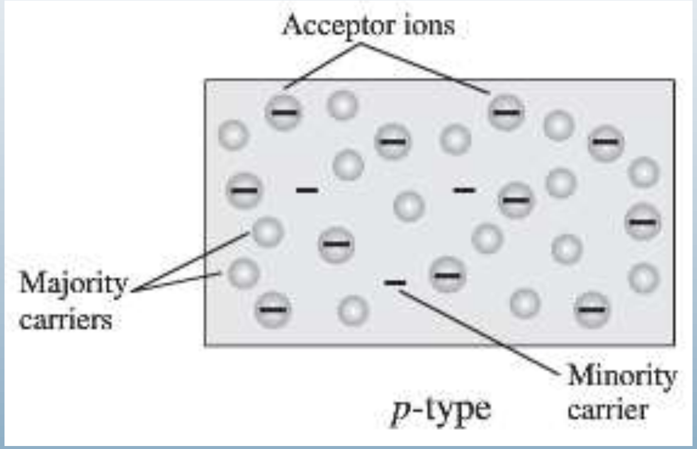


Boron impurity in p-type material.

- There is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice.
  - The resulting vacancy is called a **hole**
- The diffused impurities with three valence electrons are called **acceptor** atoms, because the resulting vacancy will readily accept a free electron

Majority and Minority Carriers

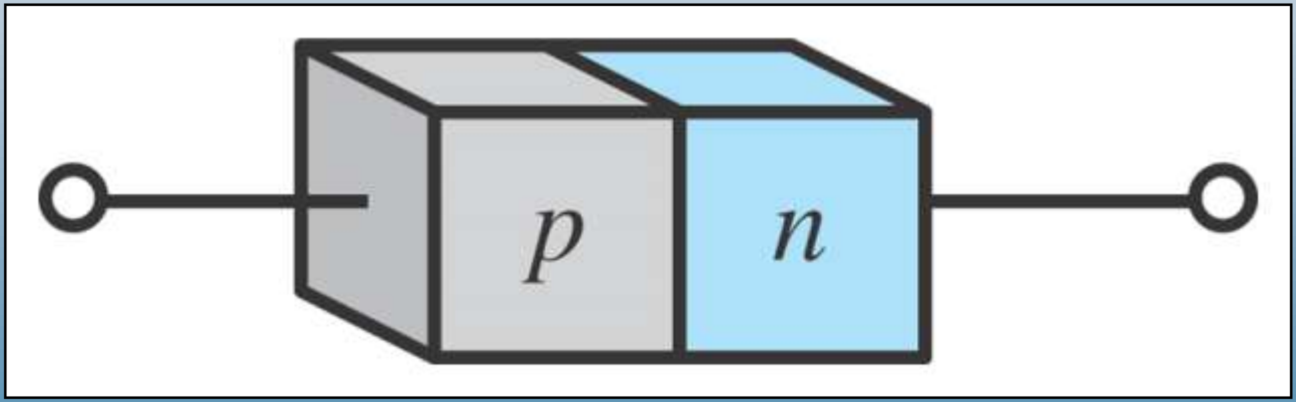




- In an n-type material, the electron is called the majority carrier and the hole the minority carrier.
- In a p-type material, the hole is called the majority carrier and the electron the minority carrier

1.6 p-n Junctions

One end of a silicon or germanium crystal can be doped as a *p*-type material and the other end as an *n*-type material.

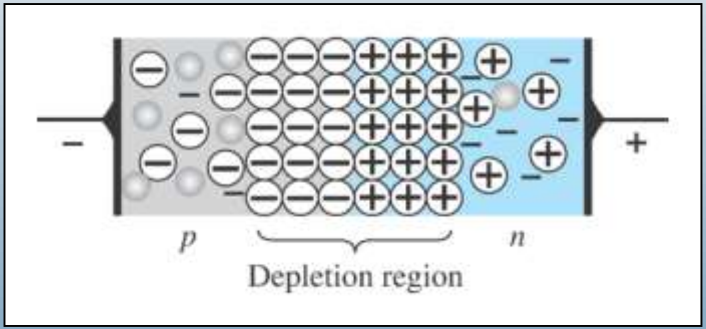


The result is a ***p-n* junction or Semiconductor Diode**

p-n Junctions

At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.

The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).



Electron migration results in a negative charge on the *p*-type side of the junction and a positive charge on the *n*-type side of the junction.

The result is the formation of a depletion region around the junction.

Diode Operating Conditions

A diode has three operating conditions:

1. **No bias** $V_D = 0V$
2. **Reverse bias** $V_D < 0V$
3. **Forward bias** $V_D > 0V$

Bias: application of an external voltage (V_D) across the two terminals of the device

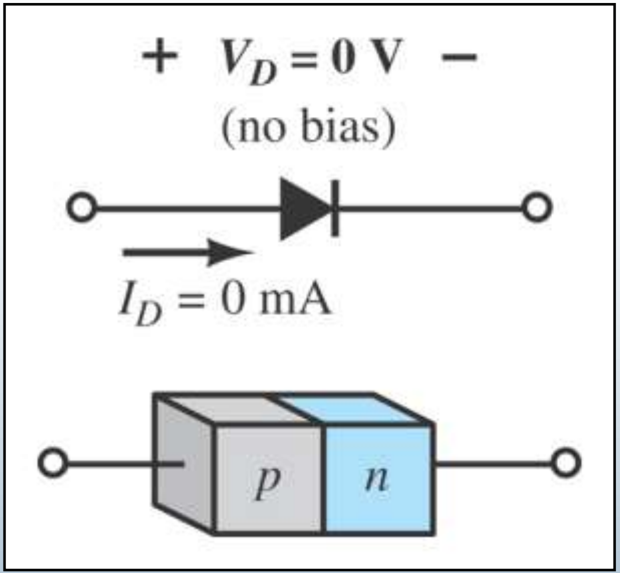
Diode Operating Conditions

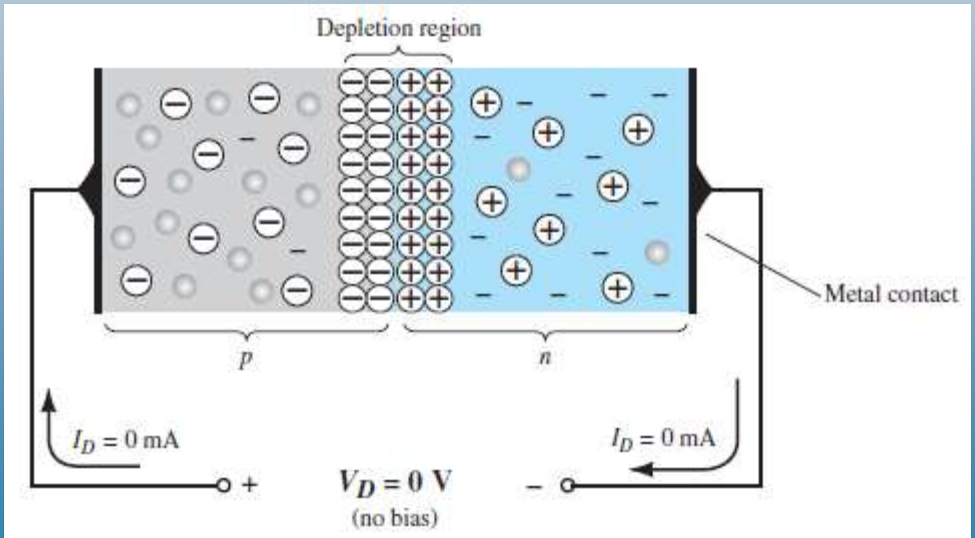
No Bias

No external voltage is applied: $V_D = 0$ V

There is no diode current: $I_D = 0$ A

Only a modest depletion region exists

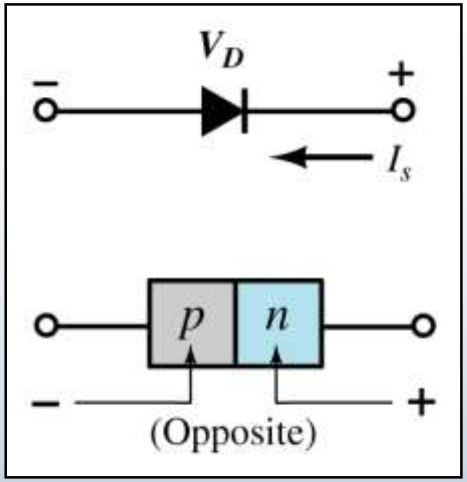




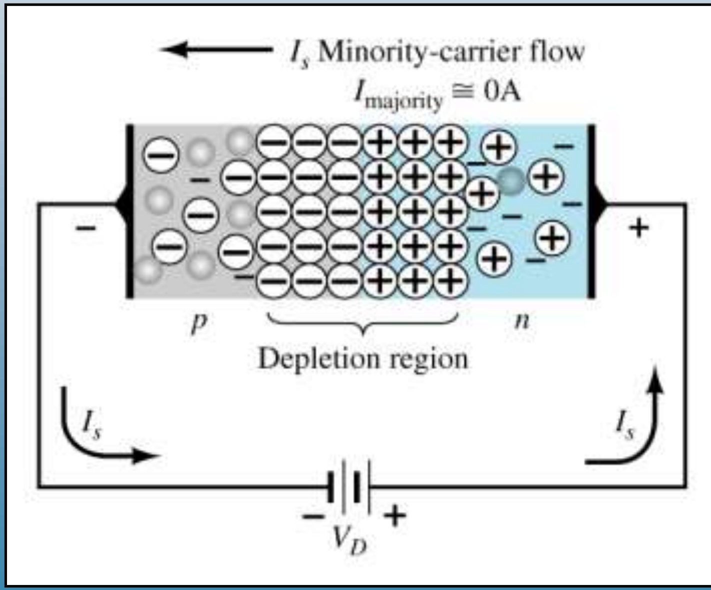
Diode Operating Conditions

Reverse Bias

External voltage is applied across the *p-n* junction in the opposite polarity of the *p*- and *n*-type materials.



- The reverse voltage causes the depletion region to widen.

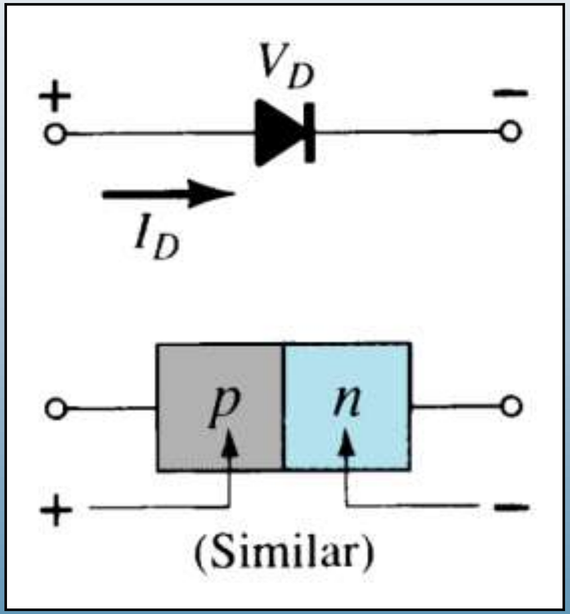


- $V_D < 0V$
- $I_{majority} = 0A$
- $I_D \cong I_{minority} = \text{small current}$

Diode Operating Conditions

Forward Bias

External voltage is applied across the *p*-*n* junction in the same polarity as the *p*- and *n*-type materials.

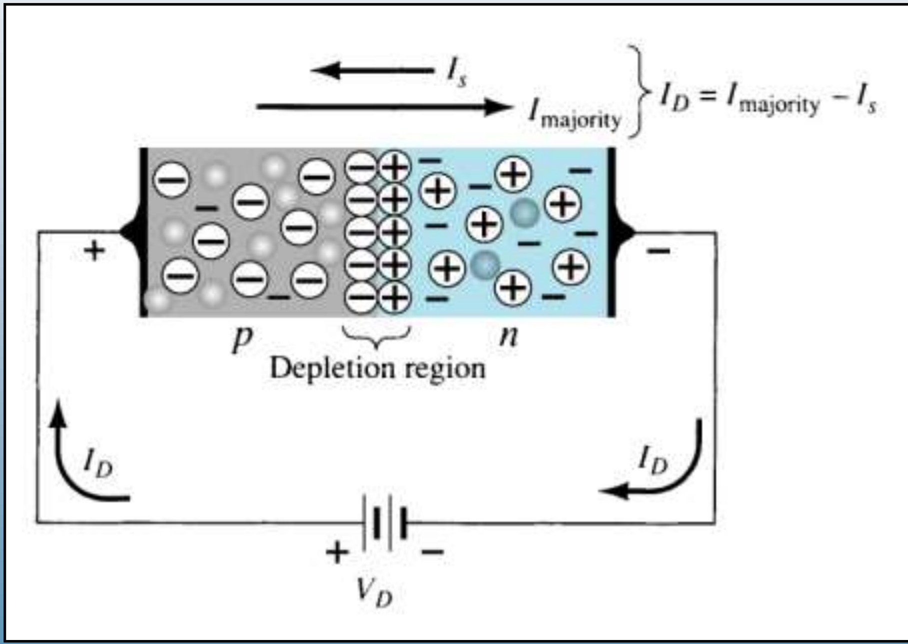


Diode Operating Conditions

Forward Bias

The forward voltage causes the depletion region to narrow.

- $V_D > 0\text{V}$
- $I_{majority} > 0\text{A}$
- $I_D \cong I_{majority} = \text{large current}$



The electrons and holes are pushed toward the *p-n* junction.

The electrons and holes have sufficient energy to cross the *p-n* junction.

Diode Current Equation

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:

$$\boxed{I_D = I_s(e^{V_D/nV_T} - 1)} \quad \text{(A)} \qquad \textbf{(1.2)}$$

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).

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

$$\boxed{V_T = \frac{kT_K}{q}} \quad \text{(V)} \qquad \textbf{(1.3)}$$

where k is Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K
T_K is the absolute temperature in kelvins $= 273 +$ the temperature in °C
q is the magnitude of electronic charge $= 1.6 \times 10^{-19}$ 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

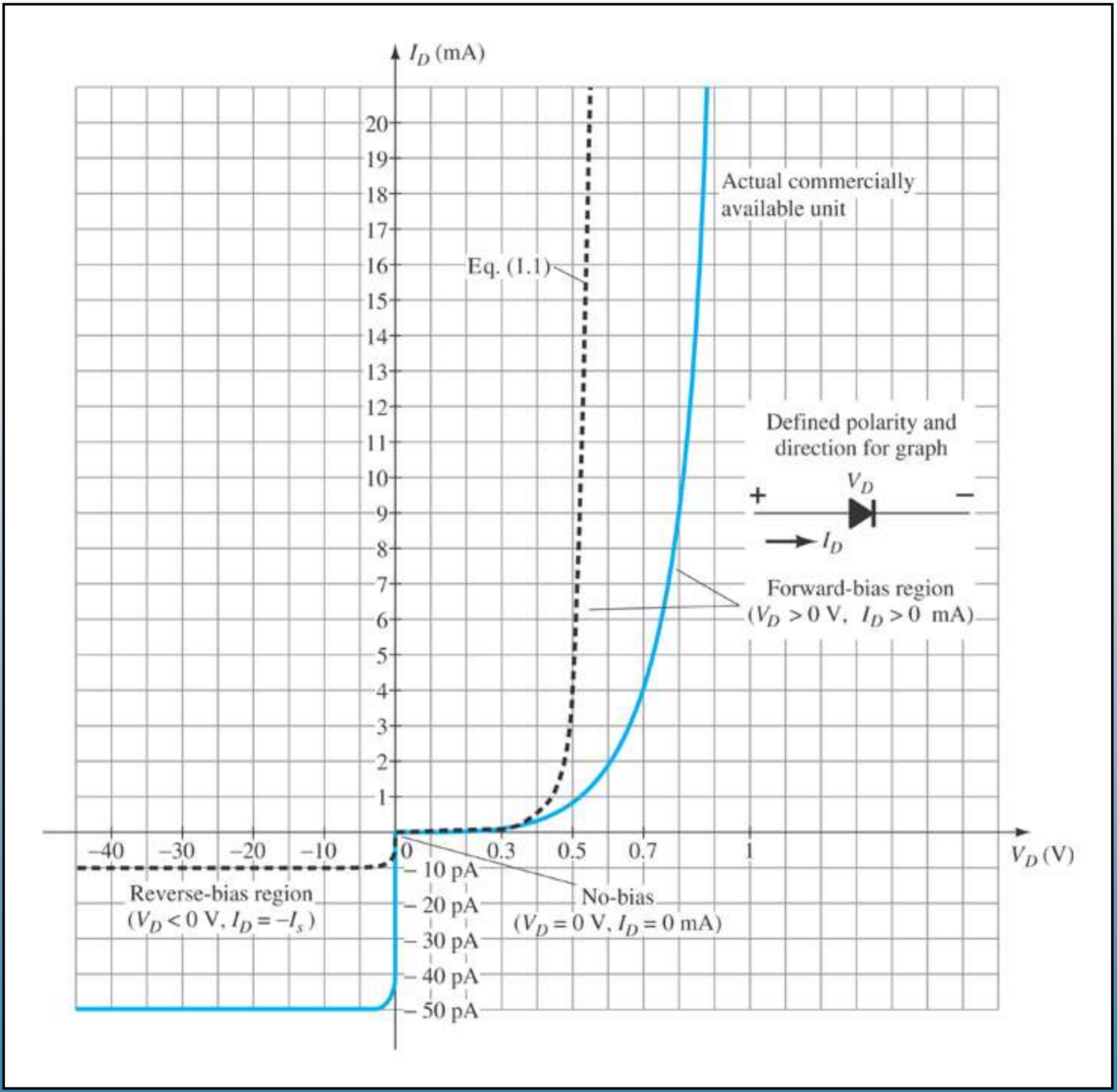
$$T = 273 + {}^\circ\mathrm{C} = 273 + 27 = 300\ \mathrm{K}$$

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

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

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

Actual/Practical Diode Characteristics

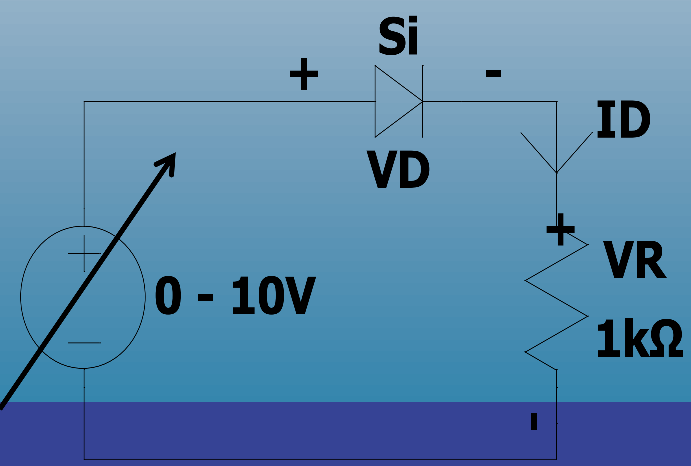


Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

Forward Bias (FB)/Short/Conduction Mode

- $V_S < 0.7V: Diode \frac{NB}{OFF}. V_D = V_S. I_D = 0mA; V_R = I_D R = 0V$
- $V_S \geq 0.7V: Diode: FB. V_D = 0.7V.$
- $V_R = V_S - 0.7V$ (KVL)
- $I_D \neq 0mA = \frac{V_R}{R};$



V_S **(V)**	I_D (mA)	$V_D(V)$	$V_R(V)$	**Diode State**
0	0	0	0	NB
0.1	0	0.1	0	NB
0.3	0	0.3	0	NB
0.5	0	0.5	0	NB
0.71	0.01	0.7	0.01	FB
1	0.3	0.7	0.3	FB
5	4.3	0.7	4.3	FB
10	9.3	0.7	9.3	FB

Forward bias condition

- $I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) = I_S e^{\frac{V_D}{nV_T}} - I_S \cong I_S e^{\frac{V_D}{nV_T}}$; $\mathrm{I_S}$ small current
- $I_1 = I_S e^{\frac{V_1}{nV_T}}$; I_1 is the diode current for voltage V_1
- $I_2 = I_S e^{\frac{V_2}{nV_T}}$; I_2 is the diode current for voltage V_2
- $\Delta V = V_2 - V_1 = nV_T \ln\frac{I_2}{I_1}$
- $\Delta V = V_2 - V_1 = 2.3\, nV_T \log\frac{I_2}{I_1}$

Forward bias condition

- Find the change in diode voltage if the current changes from 0.1μA to 10mA at room temperature with $n = 1$.
- $I_1 = 0.1\ \mu A = 0.1 \times 10^{-6} A$
- $I_2 = 10\ mA = 10 \times 10^{-3} A$
- $V_T = 26\ mV$ at room temperature
- $\Delta V = V_2 - V_1 = nV_T \ln\frac{I_2}{I_1} = 2.3\ nV_T \log\frac{I_2}{I_1}$
- $\Delta V = 1 \times 26 \times 10^{-3} \ln\frac{10\times10^{-3}}{0.1\times10^{-6}} \neq 1 \times 26 \times 10^{-3} \ln\frac{10}{0.1}$

Majority and Minority Carriers

Two currents through a diode:

Majority Carriers

The majority carriers in ***n*-type** materials are electrons.

The majority carriers in ***p*-type** materials are holes.

Minority Carriers

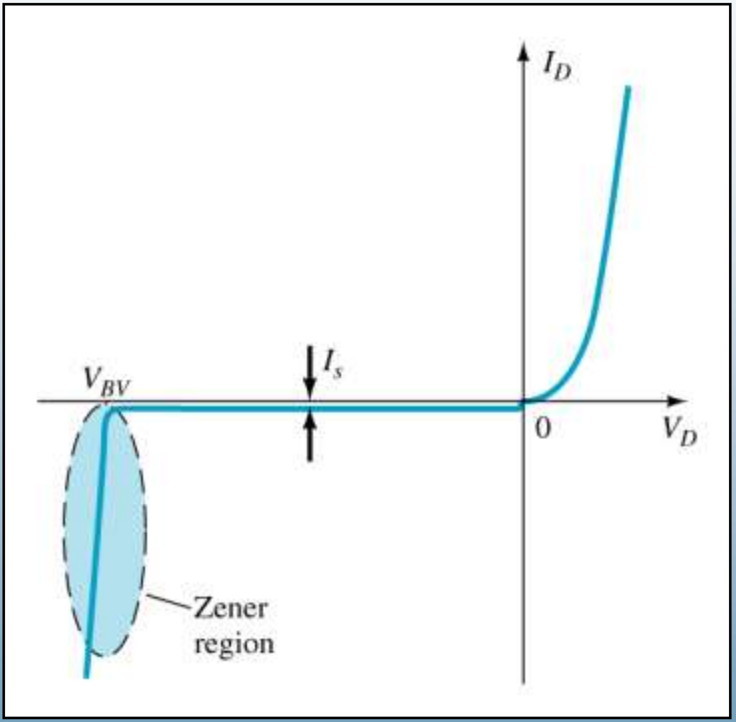
The minority carriers in ***n*-type** materials are holes.

The minority carriers in ***p*-type** materials are electrons.

Breakdown Region

The breakdown region is in the diode's reverse-bias region.

- At some point the reverse bias voltage is so large (at breakdown voltage $\boldsymbol{V_{BV}}$) the diode breaks down and the reverse current increases dramatically.
- This can be destructive if the power dissipated exceeds the "safe" level
- The maximum reverse voltage that won't take a diode into the zener region is called the **peak inverse voltage** or **peak reverse voltage.**
- Example: If breakdown voltage V_{BV} of a diode is $-60V$, the peak inverse voltage or peak reverse voltage will be $-59V$.



Forward Bias Voltage/ Threshold Voltage/ Knee Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the p-n junction. This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

gallium arsenide (GaAs) diode ≅ 1.2 V

silicon (Si) diode ≅ 0.7 V

germanium (Ge) diode ≅ 0.3 V

Other Types of Diodes

There are several types of diodes besides the standard *p-n* junction diode. Three of the more common are:

Zener diodes

Light-emitting diodes (LED)

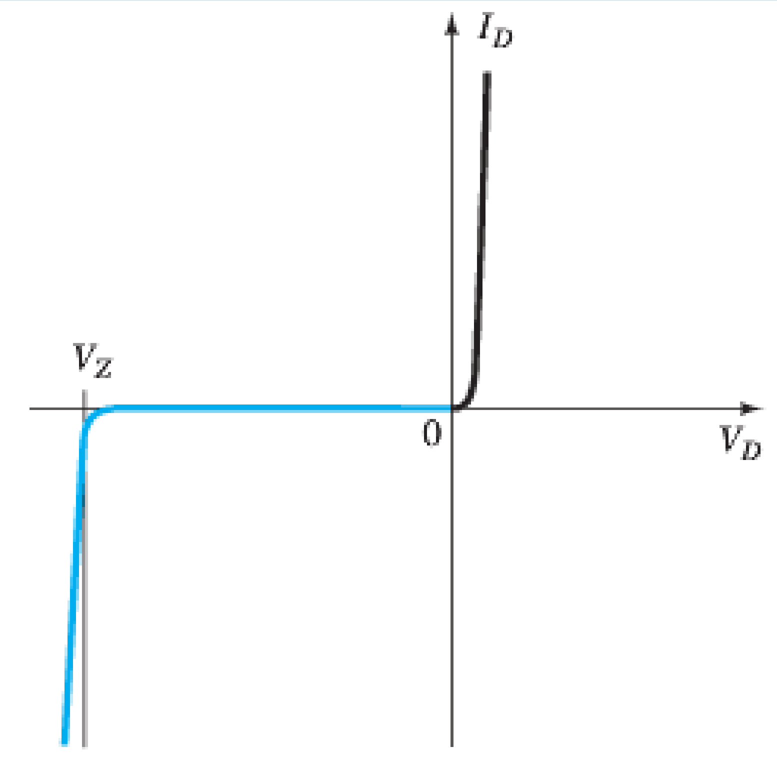
1.15 Zener Diode

A **Zener diode** is one that is designed to safely operate in its zener region; i.e., biased at the Zener voltage (V_Z).

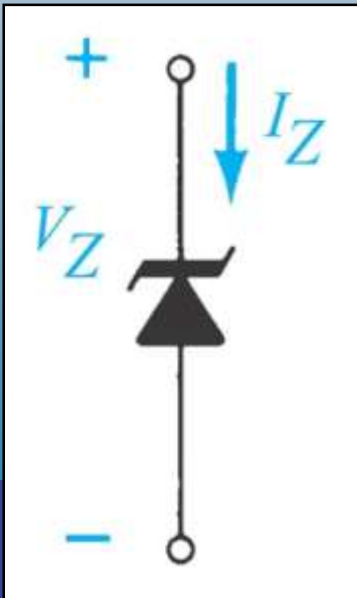
FB region: same as semiconductor diodes.

Breakdown/Zener region: Different from semiconductor diodes.

Common Zener diode voltage ratings are between 1.8V and 200V.

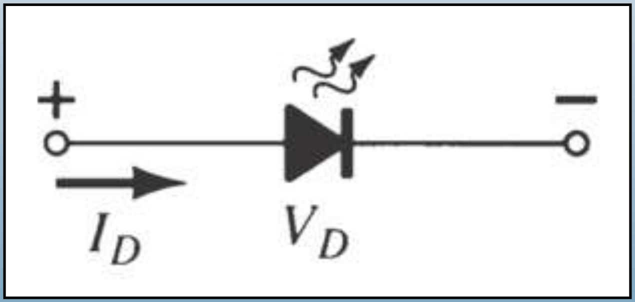


Higher doping than the semiconductor diodes.



1.16 Light-Emitting Diode (LED)

- An **LED** emits light when it is forward biased, which can be in the infrared or visible spectrum.
- LED and semiconductor diodes work exactly similar in reverse bias region.



The forward bias voltage is usually in the range of 1.5 V to 2.5 V.

Light-Emitting Diodes

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

1.8 Resistance Levels

Semiconductors react differently to DC and AC currents.

There are three types of resistance:

DC (static) resistance

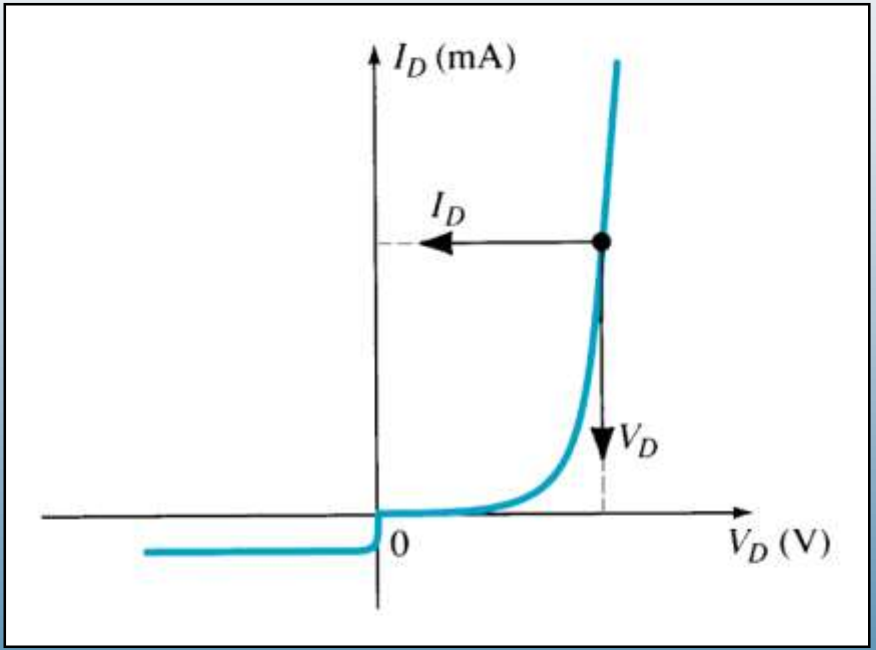
AC (dynamic) resistance

Average AC resistance

DC (Static) Resistance

For a specific applied DC voltage (V_D) the diode has a specific current (I_D) and a specific resistance (R_D).

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



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)

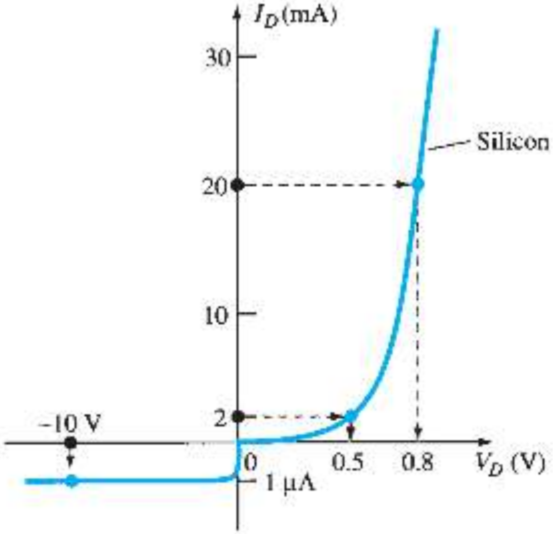


FIG. 1.24
Example 1.3.

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

$$R_D = \frac{V_D}{I_D} = \frac{10\text{ V}}{1\ \mu\text{A}} = \mathbf{10\ M\Omega}$$

AC (Dynamic) Resistance

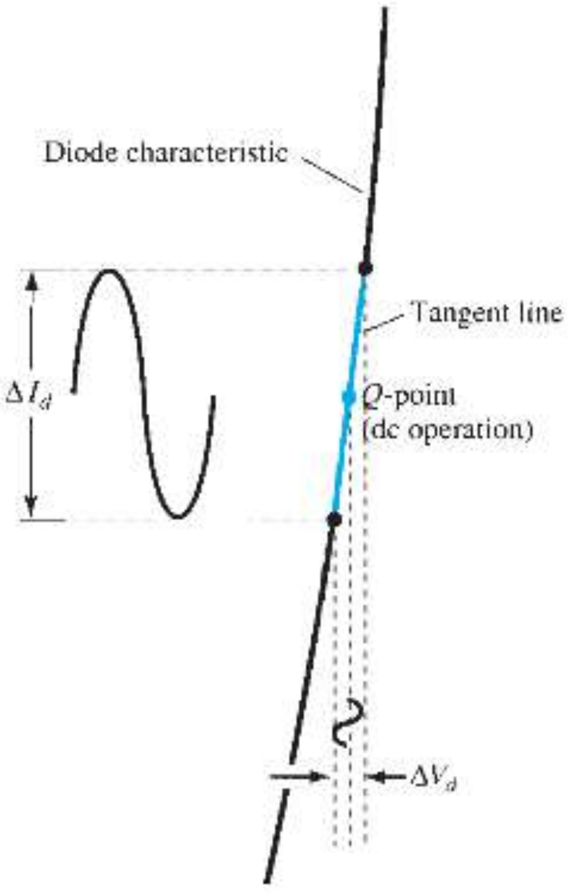


FIG. 1.25
Defining the dynamic or ac resistance.

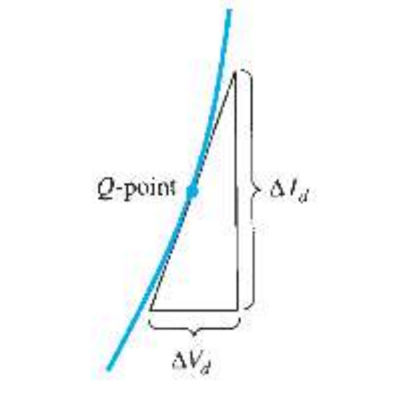


FIG. 1.26
Determining the ac resistance at a Q-point.

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

In the forward bias region: $r_d = \frac{nV_T}{I_D}$

The resistance r_d depends on the amount of current (I_D) in the diode.

Analytical Derivation of r_d

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

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

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 1.1 results in

$$\boxed{r_d = \frac{26\text{ mV}}{I_D}}$$

the dynamic resistance can be found simply by substituting the quiescent value of the diode current into the equation.

Assignment 01

- Use 11th edition of the textbook
- Total points: 100 (10 each)
- Problems:
  - ***Chapter 1***: 15, 16, 18, 19, 27, 28, 29, 31

1. Draw V-I characteristics curve of an Ideal Diode or Semiconductor (Silicon/ Germanium) Diode.

2. What do you mean by intrinsic semiconductors?

3. What do you mean by extrinsic semiconductors?

4. What are the majority and minority carriers of p-type and n-type materials?

5. What happens in a semiconductor diode in no bias condition?

6. What happens in a semiconductor diode in the forward bias condition?

7. What is break down/ Zener voltage? What is peak inverse voltage (PIV)?

8. What is forward bias voltage/knee voltage?

9. Draw the symbol of a semiconductor diode, Zener diode, and LED.

10. What are the differences between semiconductor (Si) diode and Zener diode?