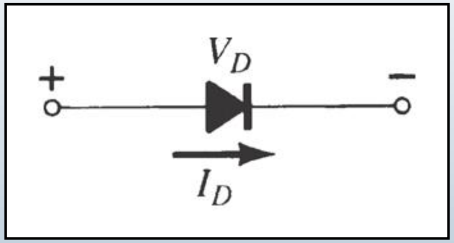
Semiconductor Diodes

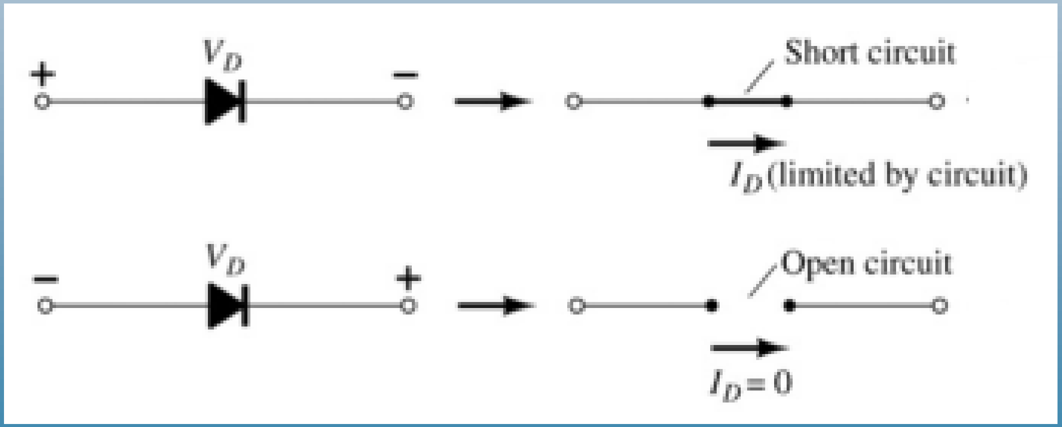
Topic 1 (Chapter 1)

Diodes

The diode is a 2-terminal device.

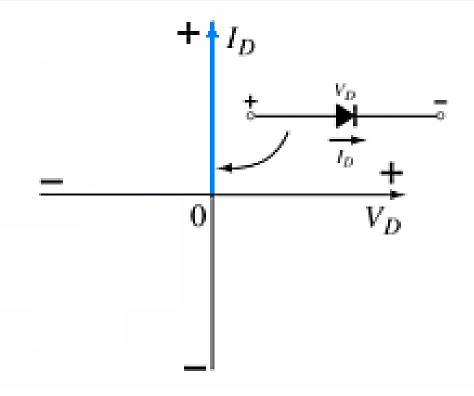


A diode ideally conducts in only one direction.



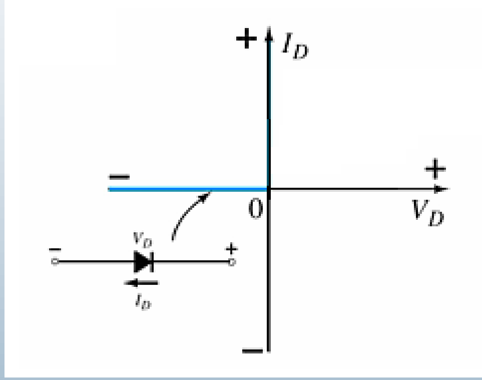
Diode Characteristics

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

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 and insulators.
- Their conductivities can be varied by changes in:
  - temperature,
  - optical excitation, and
  - impurity content.

The Periodic Table

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Semiconductor Materials

Table 1–1 Common semiconductor materials: (a) the portion of the periodic table where semiconductors occur; (b) elemental and compound semiconductors.

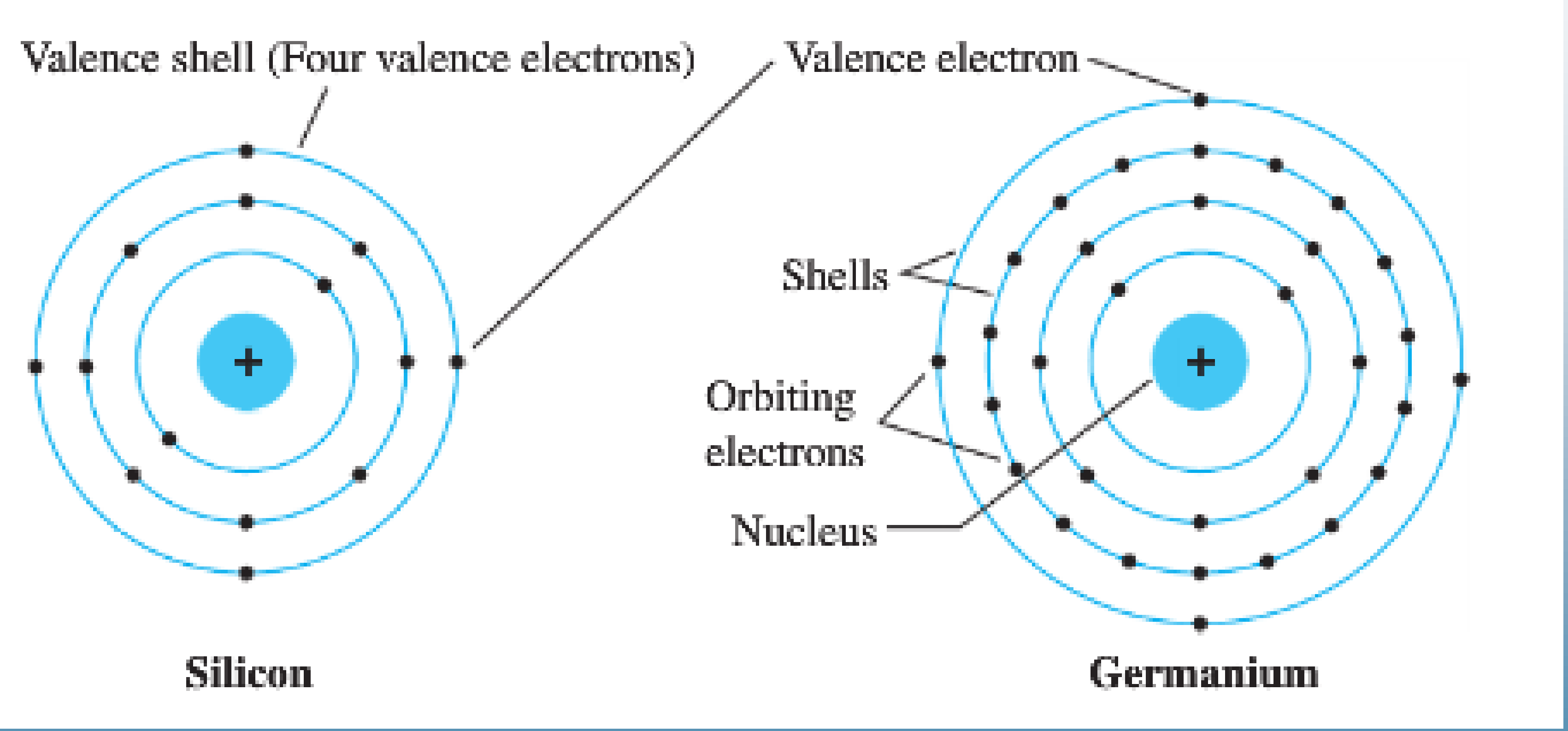
(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaN	CdS
			GaP	CdSe
			GaAs	CdTe
			GaSb	
			InP	
			InAs	
			InSb	

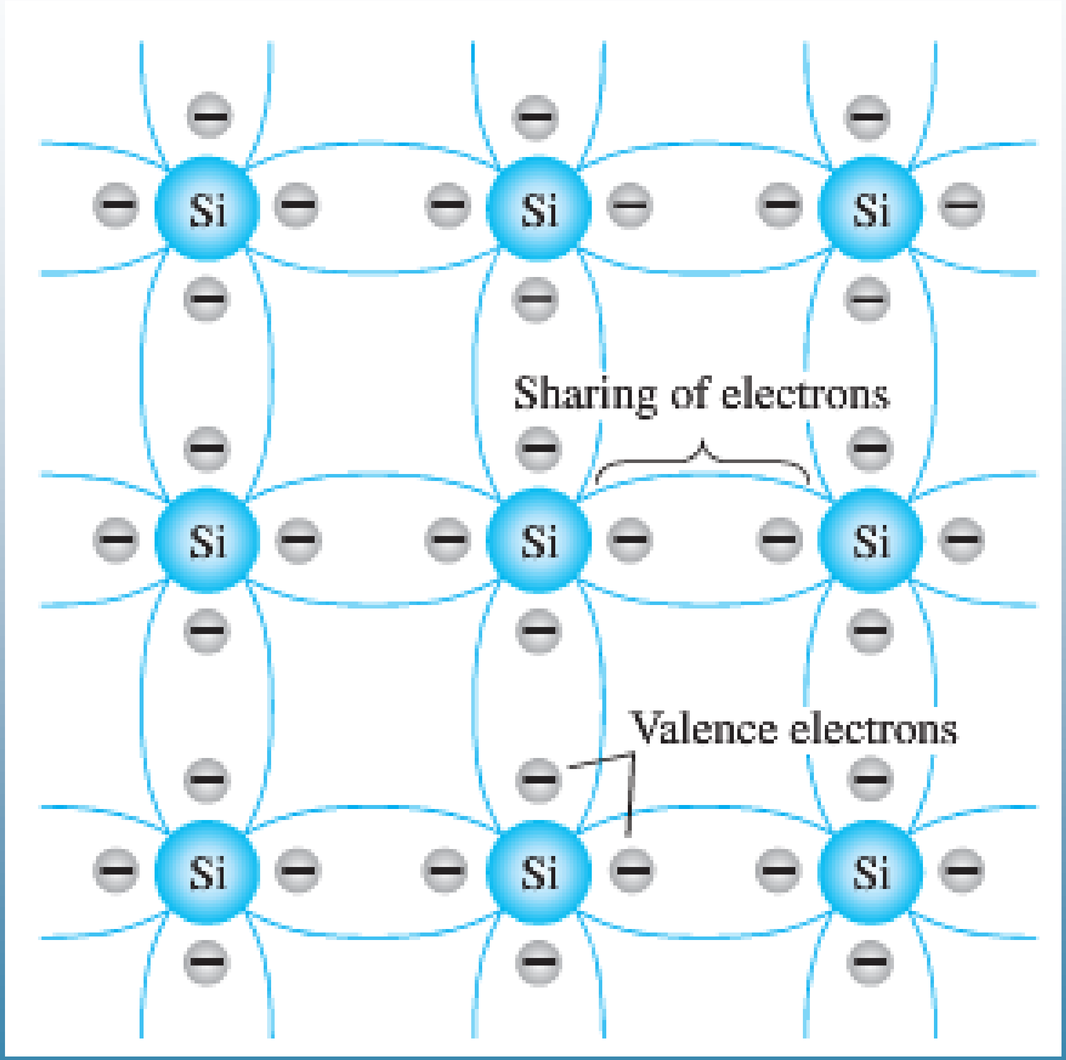
History of Popular Semiconductors

- **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.

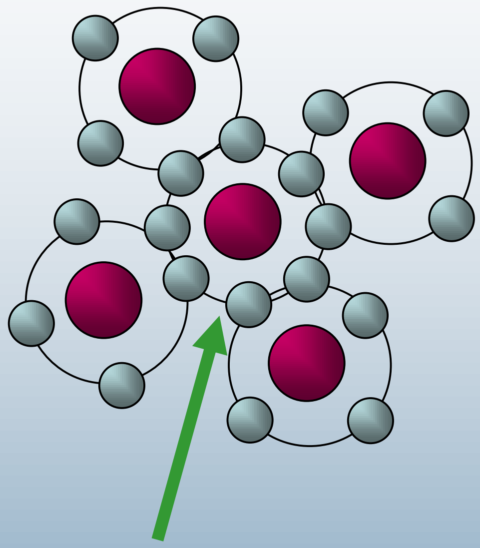
Atomic Structures of Semiconductors



Covalent bonding of the silicon atom



Silicon atoms in a crystal share electrons.



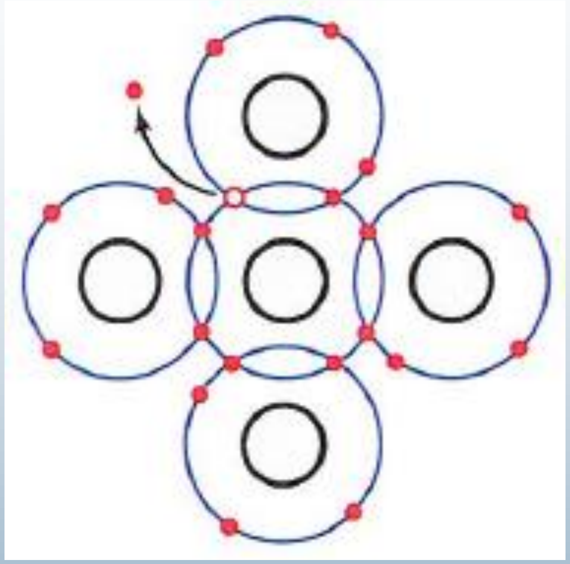
Valence saturation: n = 8

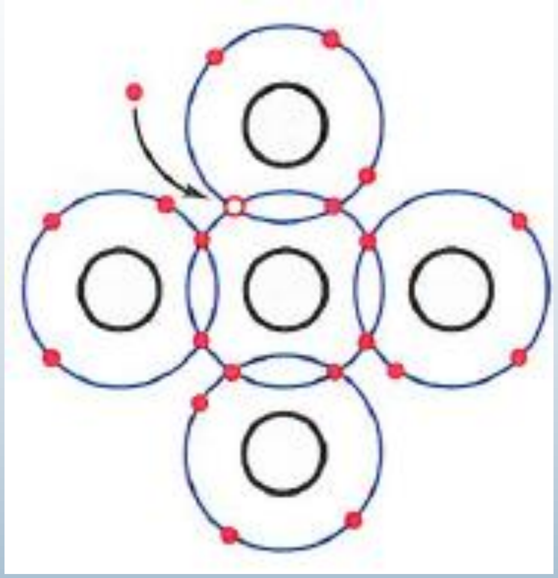
Because the valence electrons are bound, a silicon crystal at room temperature is almost a perfect insulator.

Intrinsic Semiconductors

- A pure semiconductor
- A silicon crystal is intrinsic if every atom in the crystal is a silicon atom

Electron Hole Pair Generation and Recombination

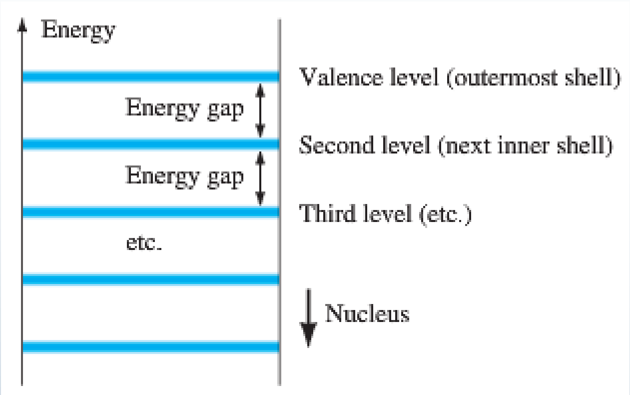




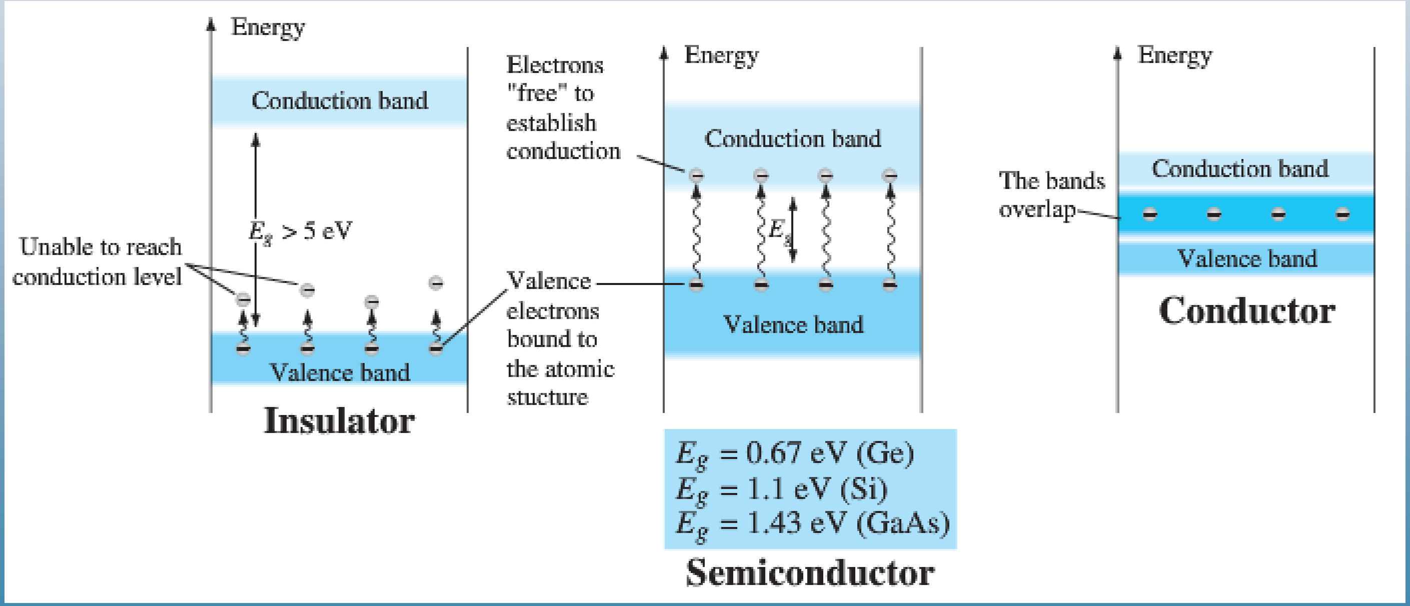
- Valence electrons can absorb sufficient energy (from light or heat) to break the covalent bonds and assume the “free” state.
  - These free electrons are called **intrinsic carriers**
- Higher temperatures creates more intrinsic carriers – hence higher conductivity

ENERGY LEVELS

- The farther an electron is from the nucleus, the higher is the energy state



(a) Discrete energy levels in isolated atomic structures



(b) conduction and valence bands of an insulator, a semiconductor, and a conductor.

Usage of Semiconductor Bandgap

- The bandgap determines the wavelengths of light that can be absorbed or emitted by the semiconductor.
  - For example, the band gap of GaAs is about 1.43 electron volts (eV), which corresponds to light wavelengths in the near **infrared**.
  - In contrast, GaP has a band gap of about 2.3 eV, corresponding to wavelengths in the **green** portion of the spectrum.
- LEDs and lasers can be constructed with wavelengths over a broad range of the spectrum.

Extrinsic Semiconductors

- 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:**

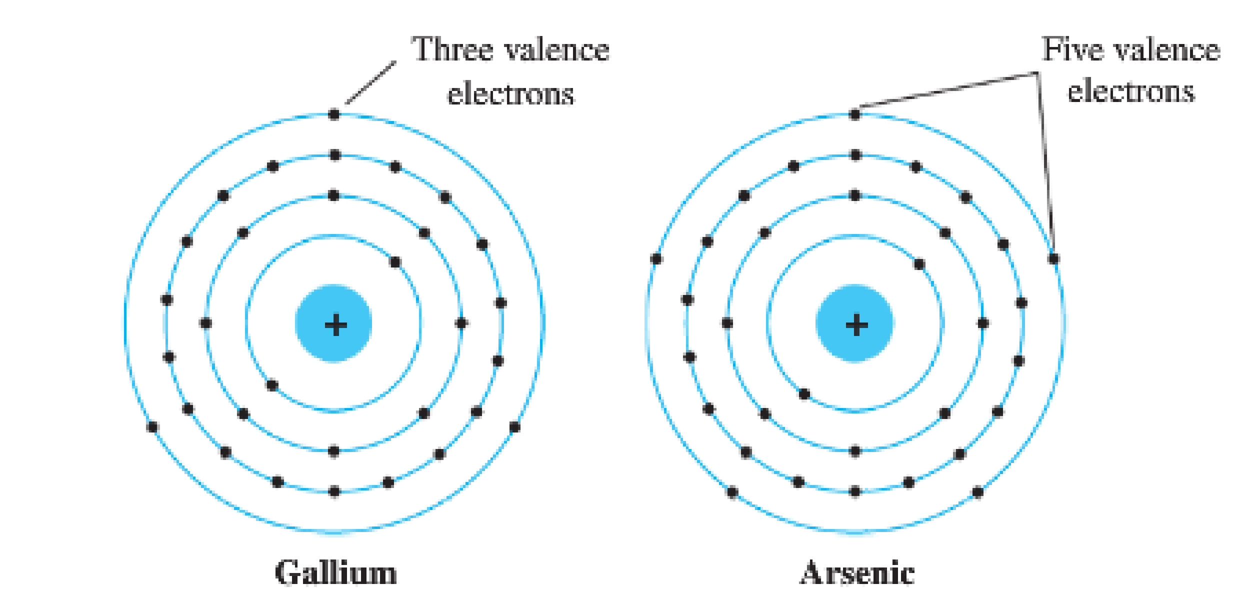
n-type

p-type

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

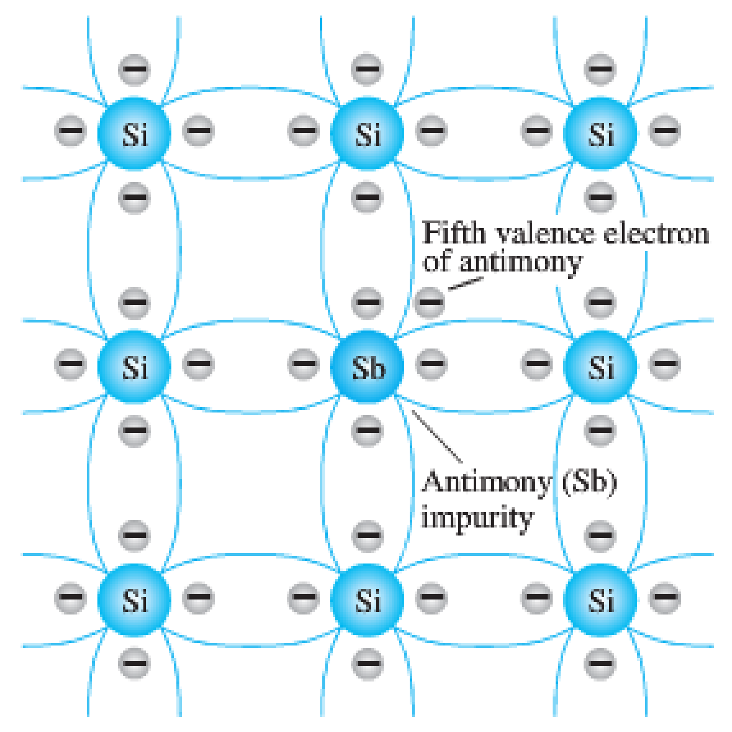
***p*-type** materials contain an excess of valence band holes.

Atomic Structures of Impurities

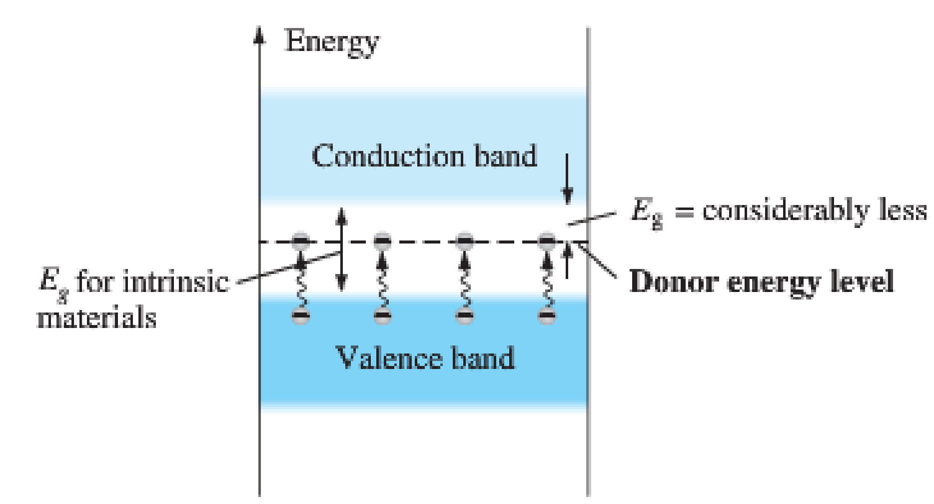


- p-type material is created by adding impurity elements such as B, Ga, and In
- n-type material is created by adding impurity elements such as Sb, As, and Ph

n -Type Material



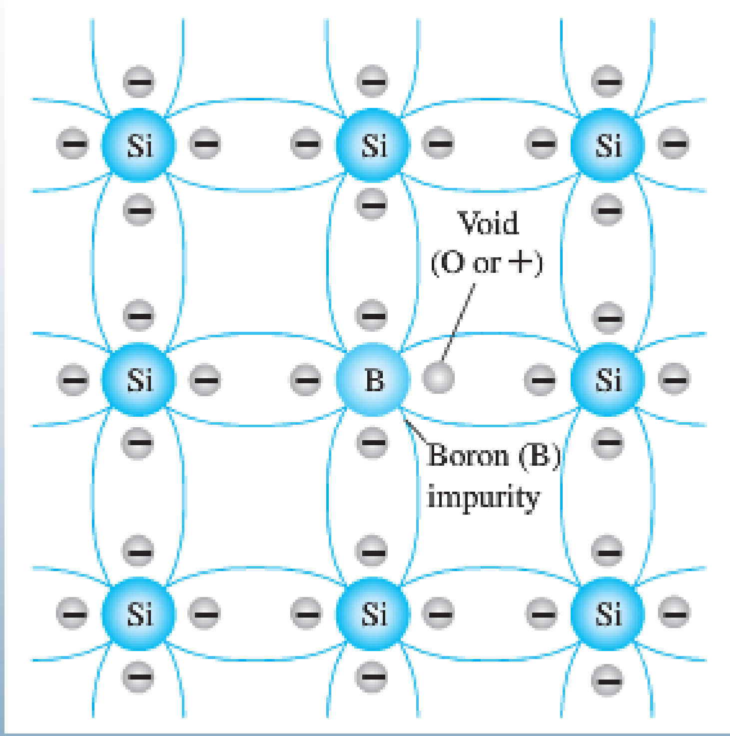
Antimony impurity in n-type material.



Effect of donor impurities on the energy band structure.

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

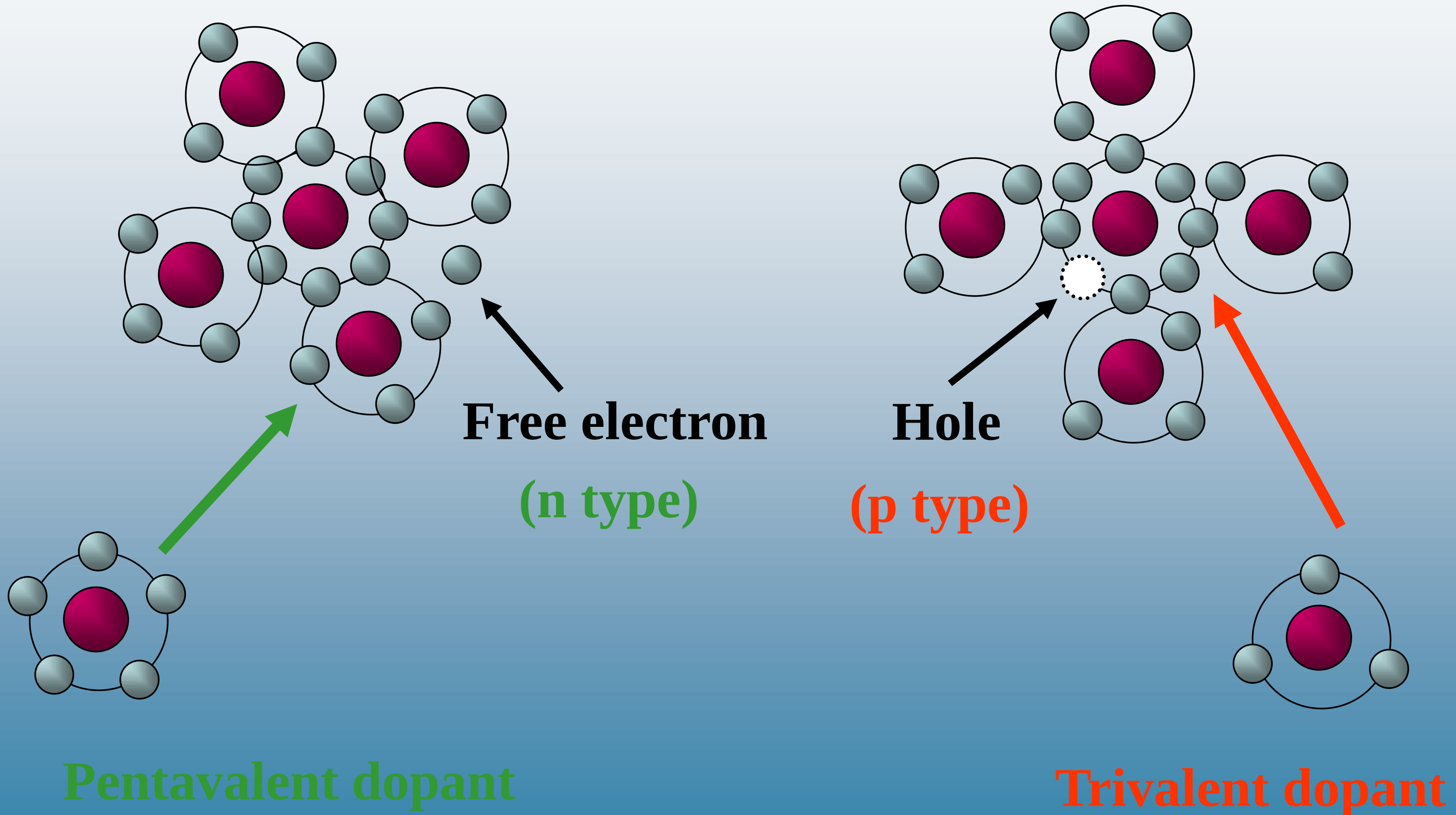
p-Type Material



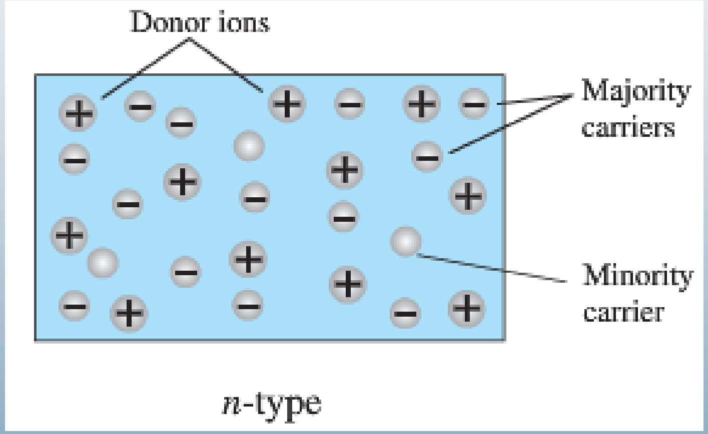
Boron impurity in p-type material.

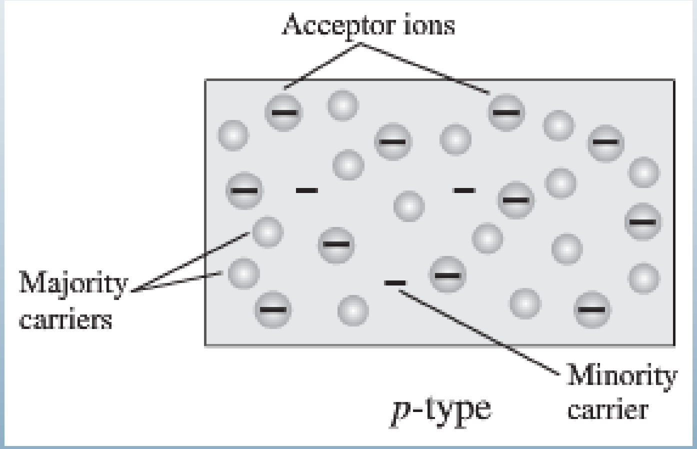
- There is now an insufficient number of electrons to complete the covalent bonds of the newly formed lattice.
  - The resulting vacancy is called a **hole**
- The diffused impurities with three valence electrons are called **acceptor** atoms, because the resulting vacancy will readily accept a free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

Silicon crystals are doped to provide permanent carriers.

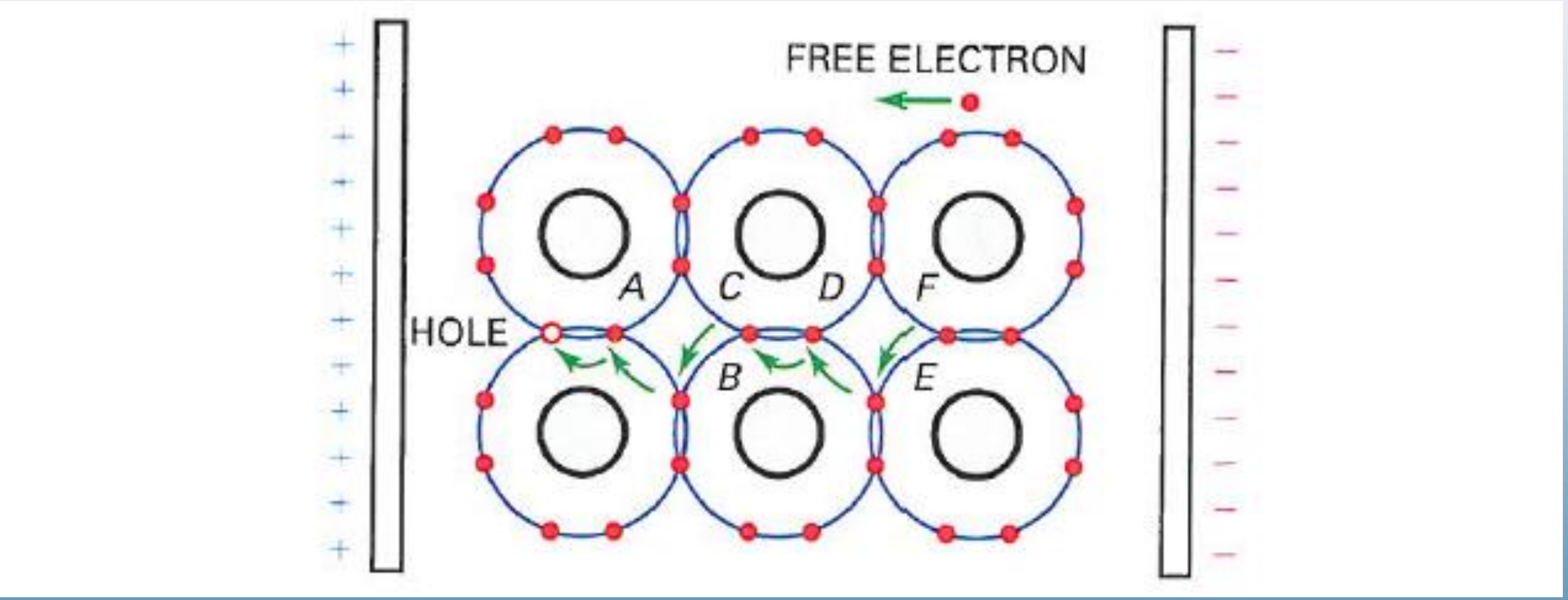


Majority and Minority Carriers

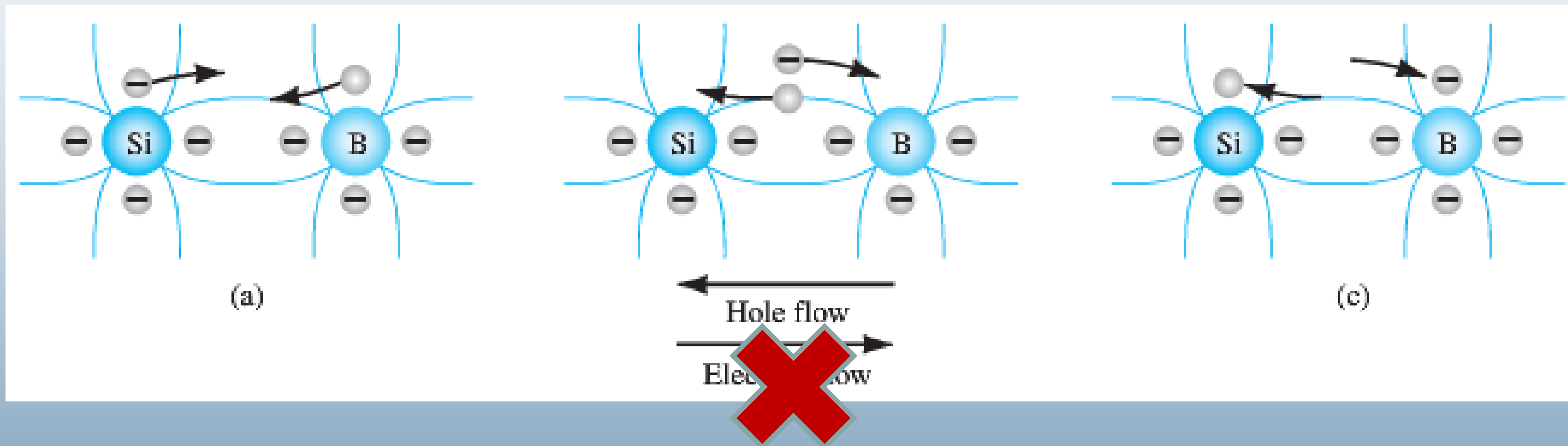




Flow of Electrons and Holes



Electron versus Hole Flow



Electrical Classification of Materials

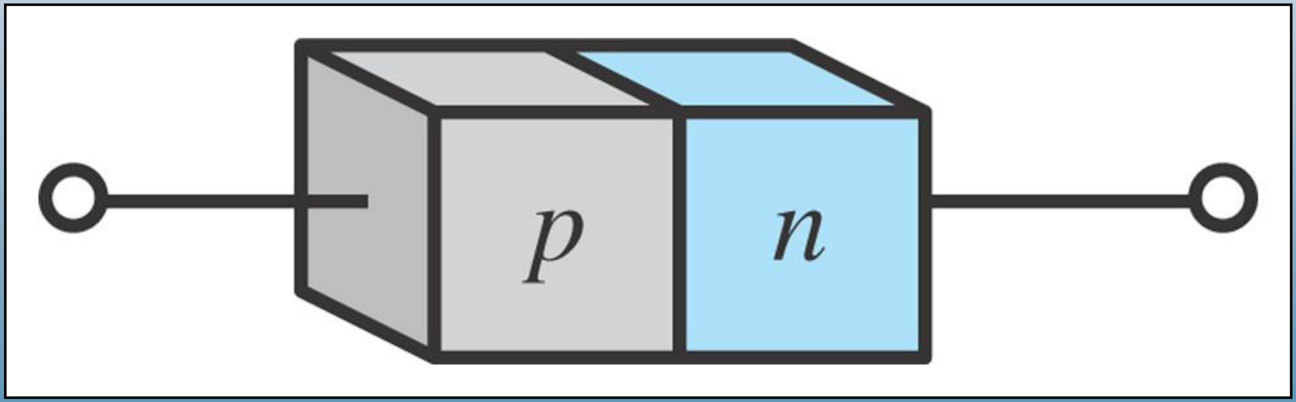
- Materials
  - Conductors
  - Semiconductors
    - Intrinsic (Pure)
    - Extrinsic (Doped or Impure)
      - n-type (Pentavalent impurities added, e.g., Ph, As, etc.)
      - p-type (Trivalent impurities added, e.g., B, Ga, etc.)
  - Insulators

Semiconductors in Summary

- The most popular material is silicon.
- Pure crystals are <u>intrinsic</u> semiconductors.
- Doped crystals are <u>extrinsic</u> semiconductors.
- Crystals are doped to be n type or p type.
- A doped semiconductor will have mostly majority carriers and a few thermally generated *minority* carriers.
  - *Electrons* are majority carriers in n type
  - *Holes* are majority carriers in p type

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.

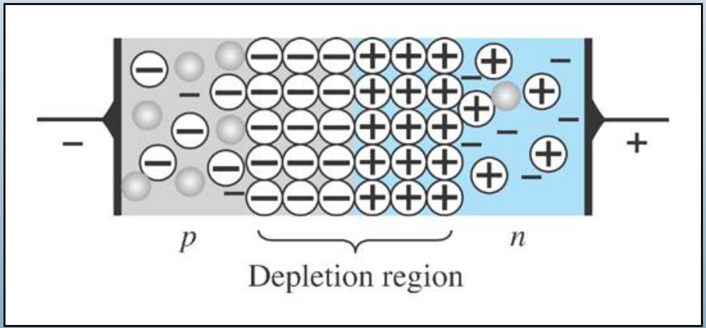


The result is a ***p-n* junction**

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:

- **No bias**
- **Reverse bias**
- **Forward bias**

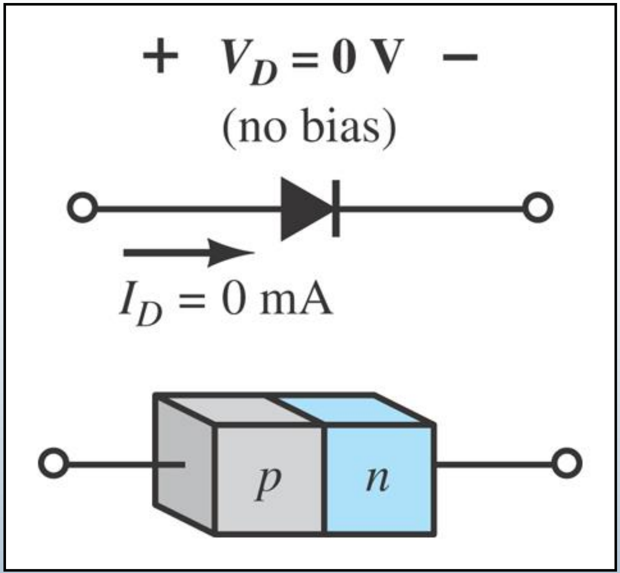
Diode Operating Conditions

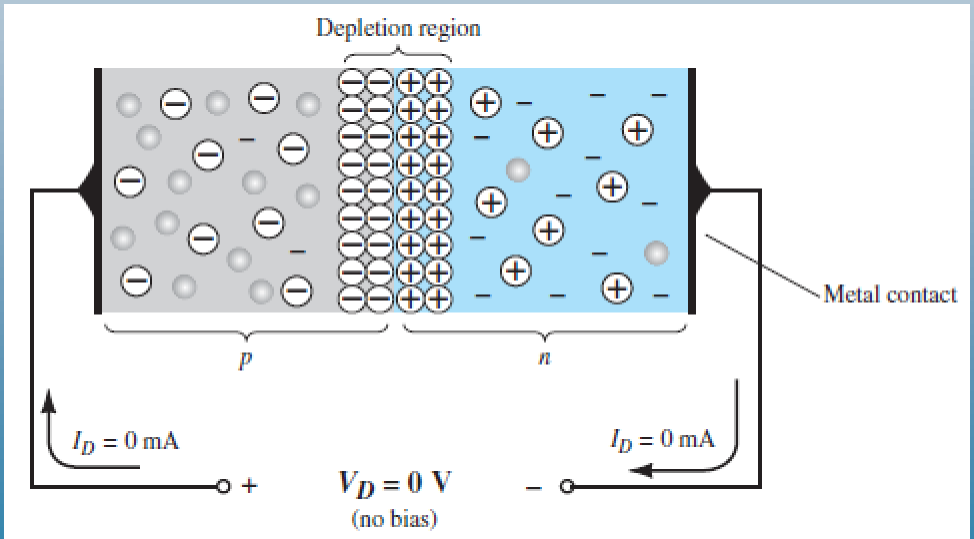
No Bias

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

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

Only a modest depletion region exists

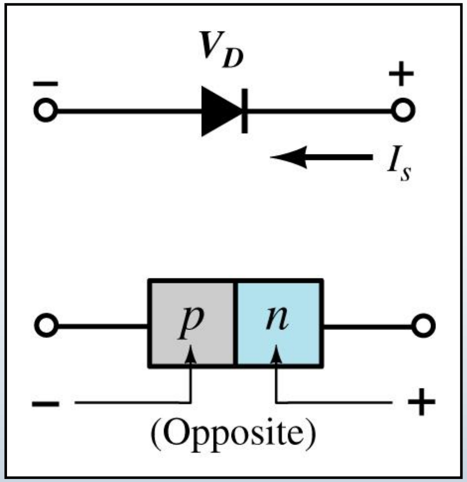




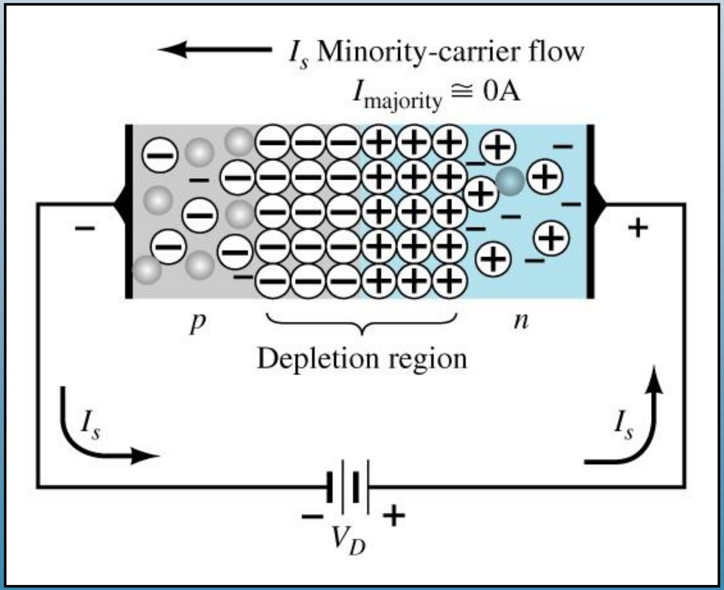
Diode Operating Conditions

Reverse Bias

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



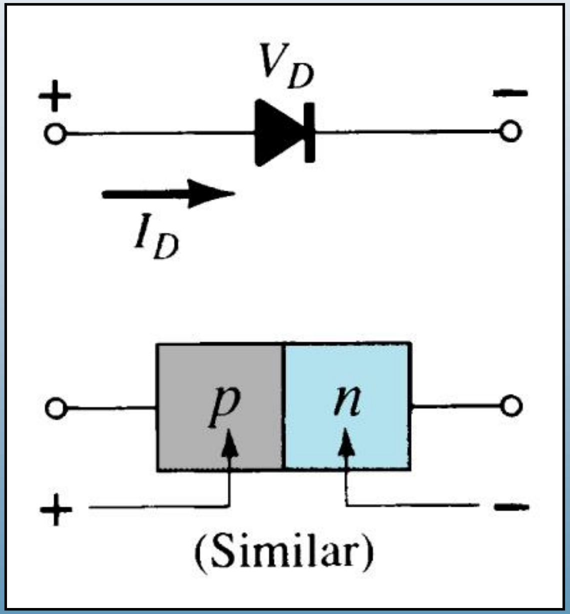
The reverse voltage causes the depletion region to widen.



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.

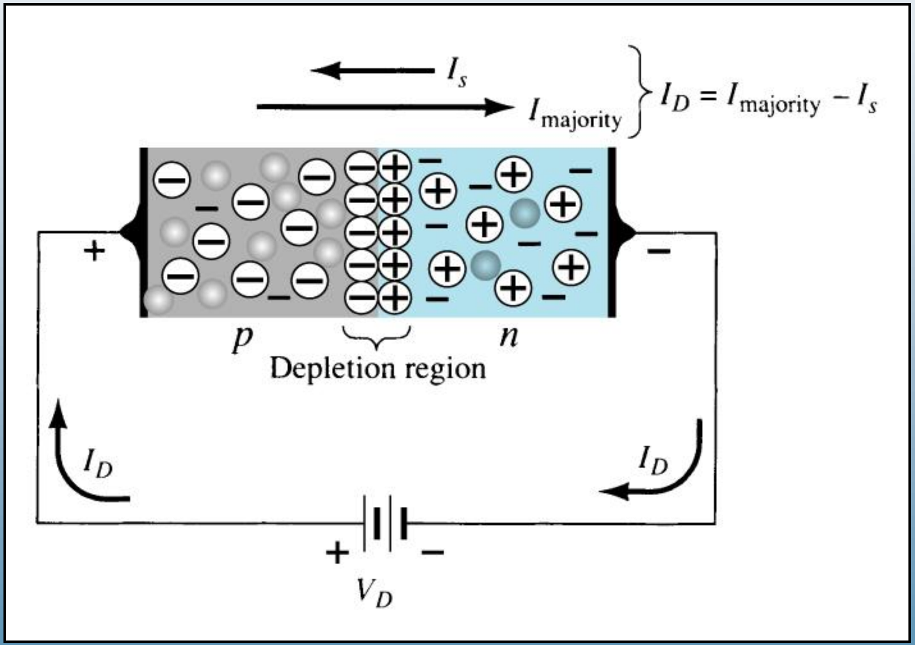


Diode Operating Conditions

Forward Bias

The forward voltage causes the depletion region to narrow.

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

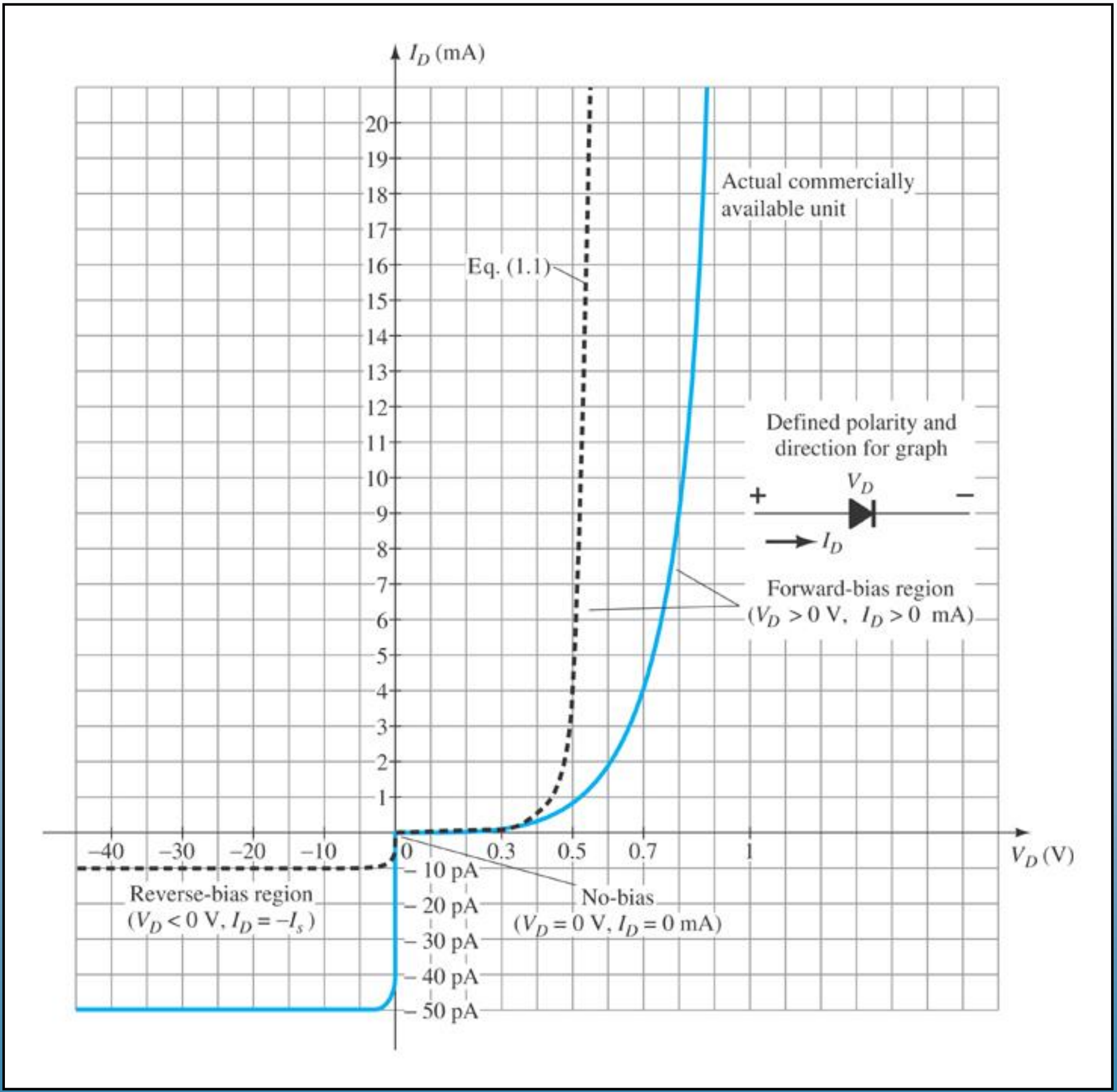
$$T = 273 + {}^{\circ}\mathrm{C} = 273 + 27 = 300\ \mathrm{K}$$

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

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

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

Actual Diode Characteristics

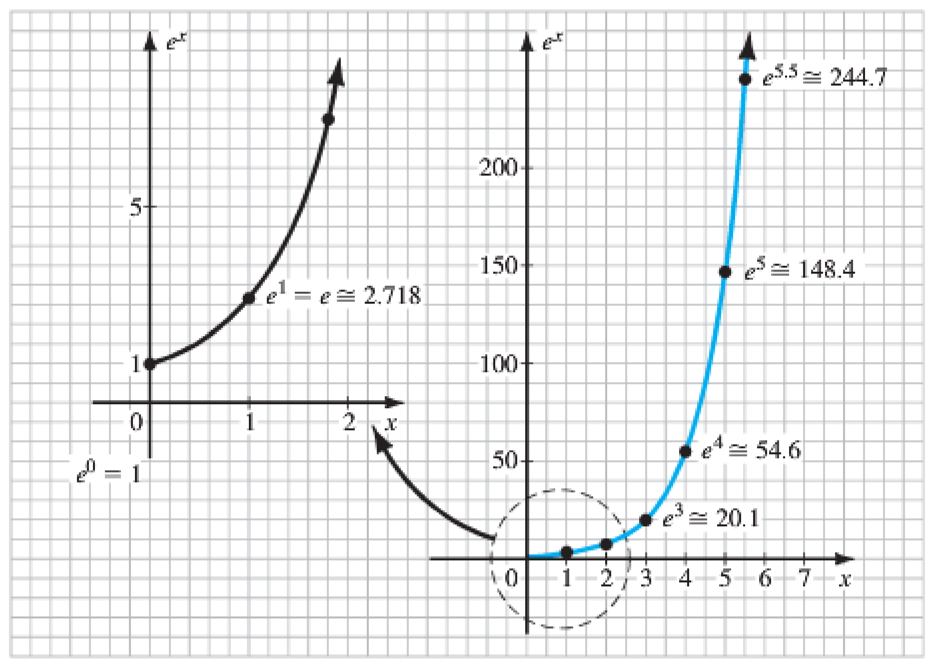


Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

Diode Current Approximations

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



$$I_D = I_s e^{V_D/nV_T} - I_s$$

V_D	$e^{\frac{V_D}{V_T}}$	Value
$-25\ mV$	e^{-1}	0.37
$-50\ mV$	e^{-2}	0.14
-75 mV	e^{-3}	0.05
-100 $mV = -0.1V$	e^{-4}	0.02

$$I_D \cong I_s e^{V_D/nV_T} \qquad (V_D \text{ positive})$$

$$I_D \cong -I_s \qquad (V_D \text{ negative})$$

Actual Reverse Saturation Current

- The actual reverse saturation current of a commercially available diode will normally be measurably larger than I_s due to a wide range of factors that include
  - surface leakage currents
  - higher doping levels that result in increased levels of reverse current
  - temperature sensitivity

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

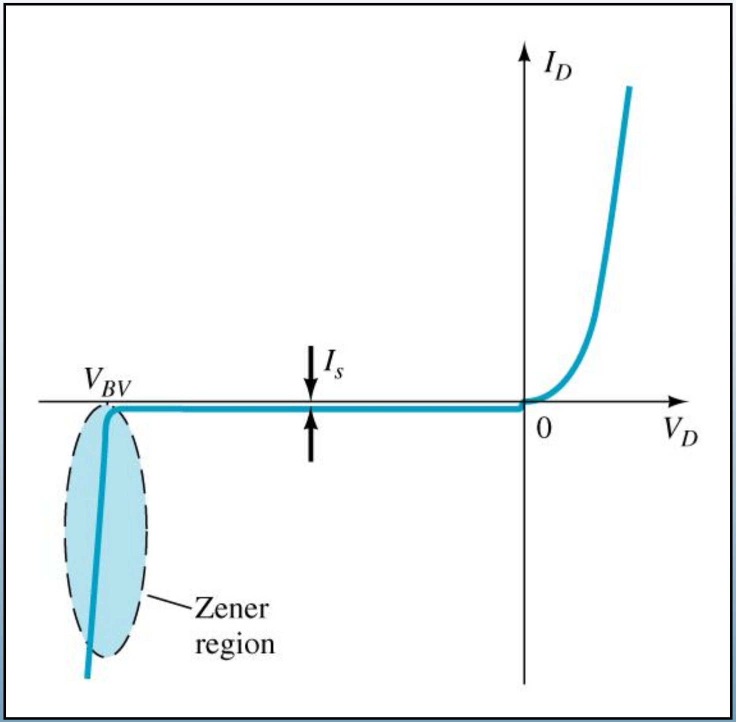
The minority carriers in ***n*-type** materials are holes.

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.**



- **Two mechanisms:**
  - ***Zener breakdown:*** Due to high electric field at the depletion region (up to about 5V)
  - ***Avalanche breakdown:*** Due to high kinetic energy of electrons (5V and above)

Zener Voltage

- The breakdown voltage (V_{BV}) can be reduced by increasing the doping levels in the p - and n -type materials.
- As V_{BV} decreases to low levels, such as ~5V, Zener breakdown becomes the dominant factor compared to avalanche breakdown.
  - The strong electric field in the region of the junction can disrupt the bonding forces within the atom and "generate" carriers.
- This sharp change in the characteristic at any breakdown voltage is called the Zener region
  - Diodes employing this unique portion of the characteristic of a p–n junction are called **Zener diodes**
    - **The actual breakdown mechanism can be either zener or avalanche**
- The voltage that causes a diode to enter the zener region of operation is called the **zener voltage (V_Z)**.

Forward Bias 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.

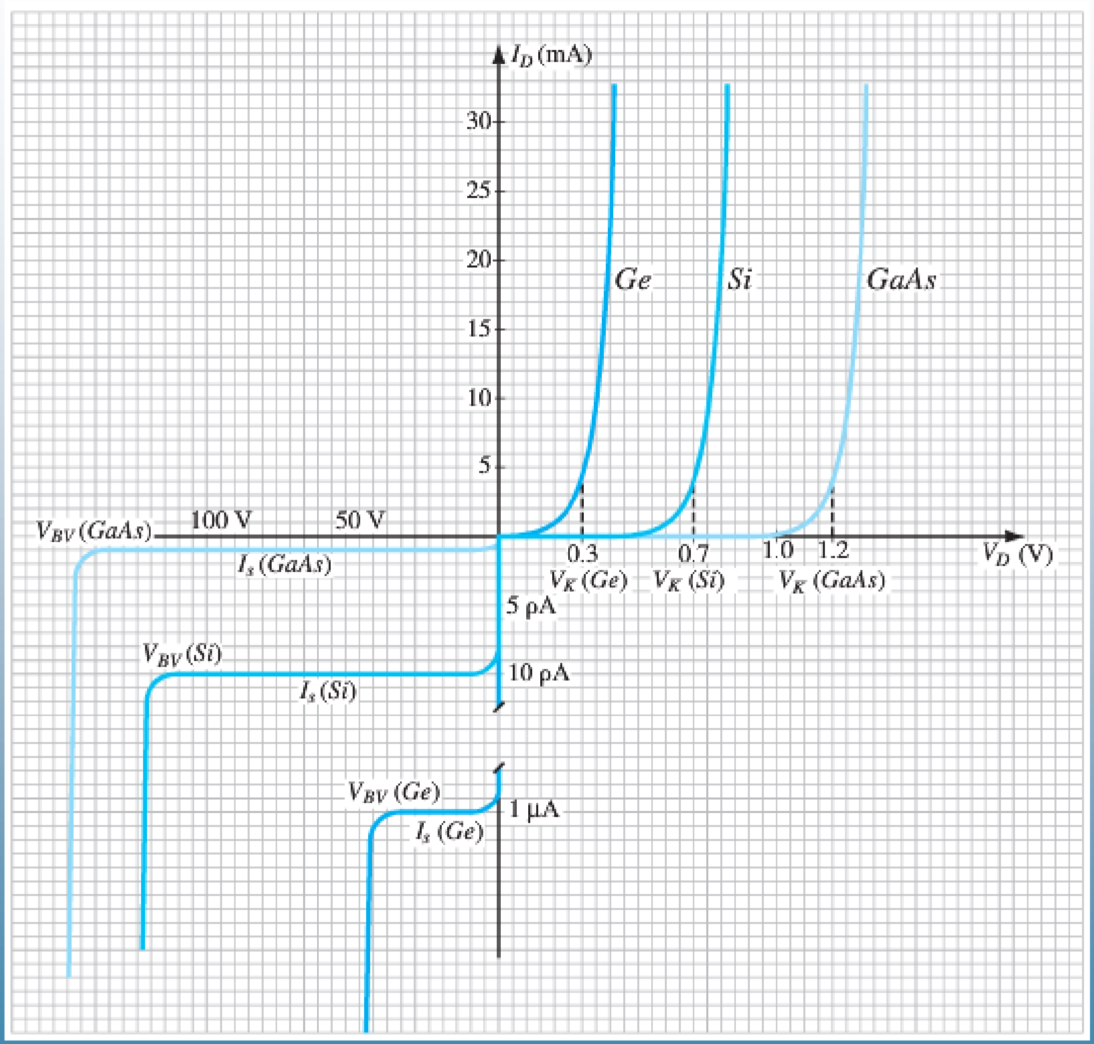
The forward bias voltage required for a:

gallium arsenide diode ≅ 1.2 V

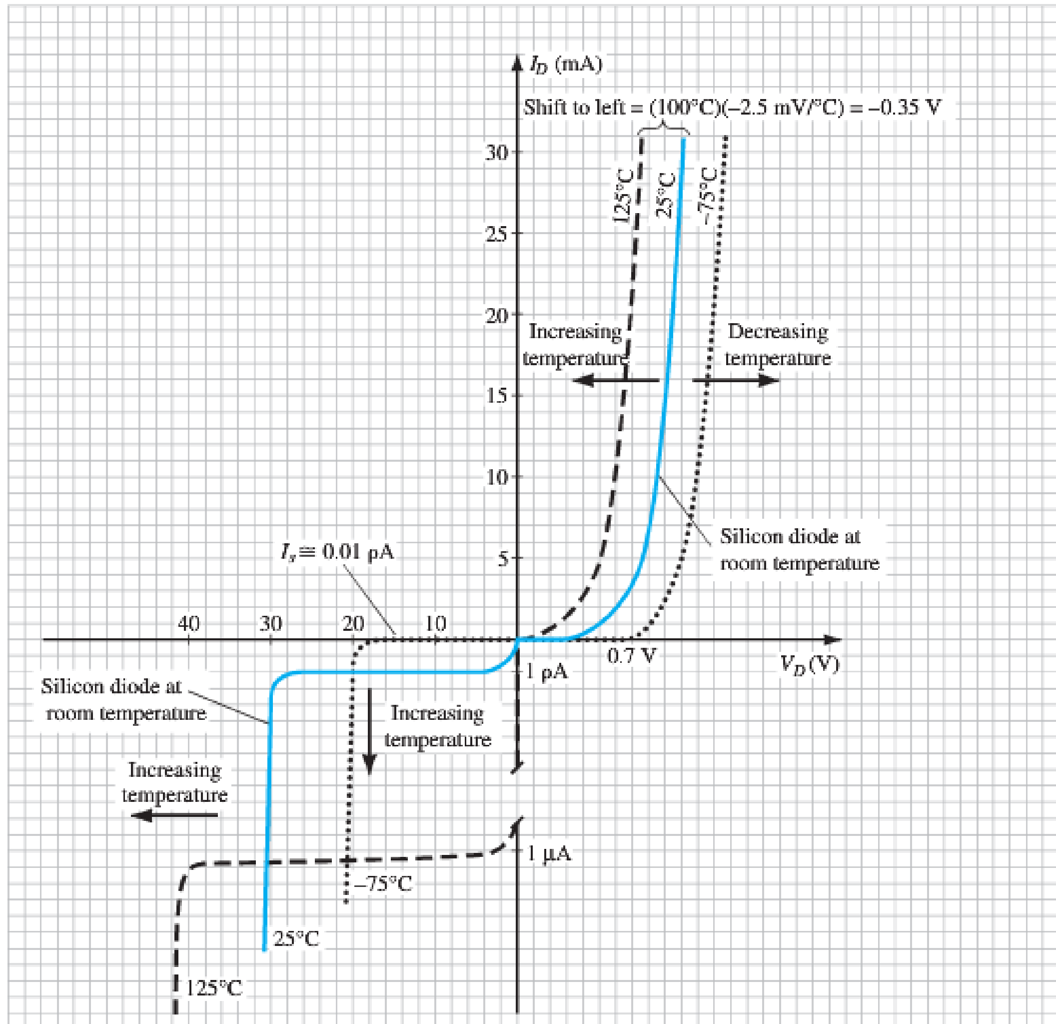
silicon diode ≅ 0.7 V

germanium diode ≅ 0.3 V

Comparison of Ge, Si, and GaAs diodes



Temperature Effects



- **As temperature increases it adds energy to the diode.**
  - It reduces the required forward bias voltage
  - It increases the amount of reverse current and reverse breakdown voltage.
- The reverse current of a silicon diode doubles for every 10°C rise in temp.
- ***Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.***

Other Types of Diodes

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

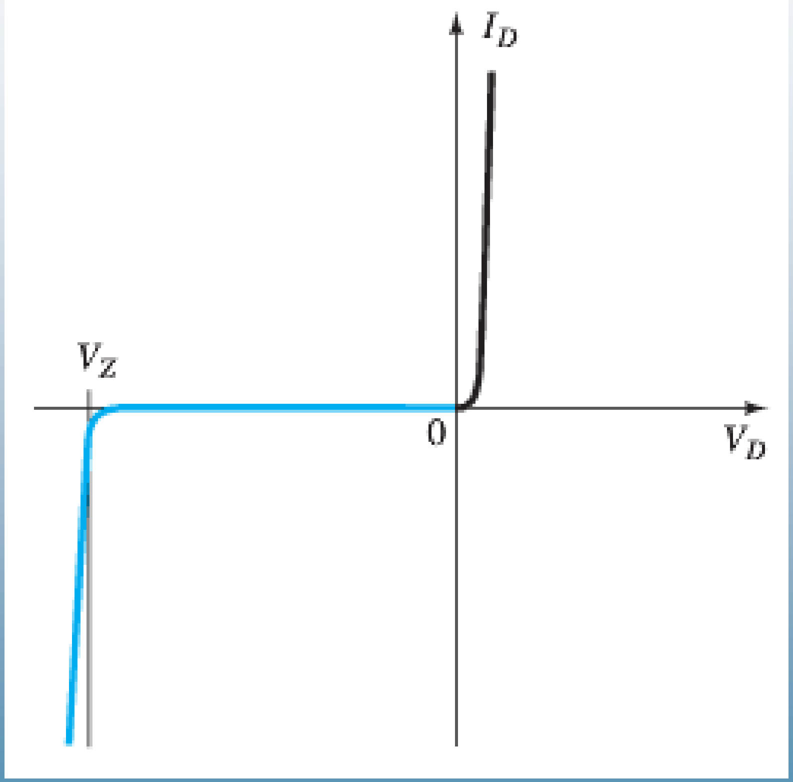
Zener diodes

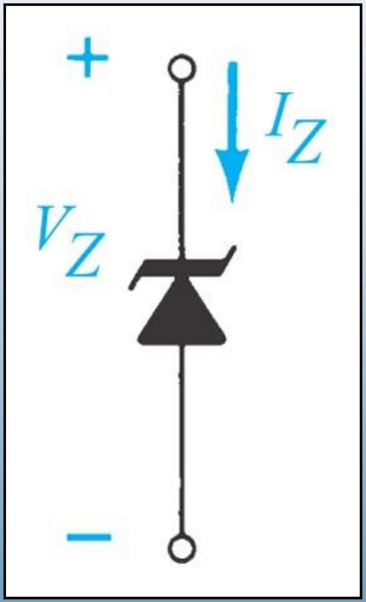
Light-emitting diodes

Diode arrays

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).

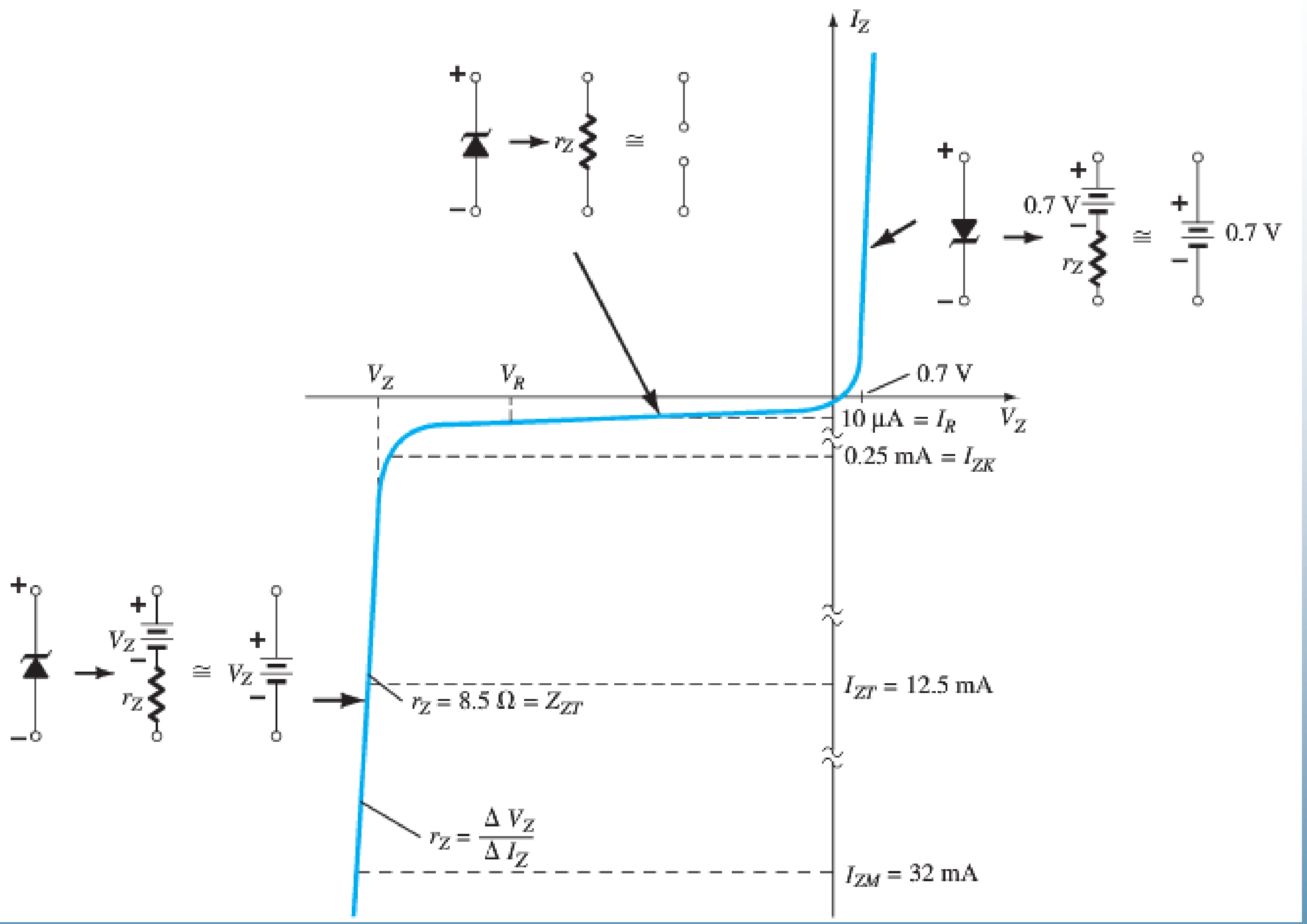




Common zener diode voltage ratings are between 1.8 V and 200 V

Zener Diode Characteristics

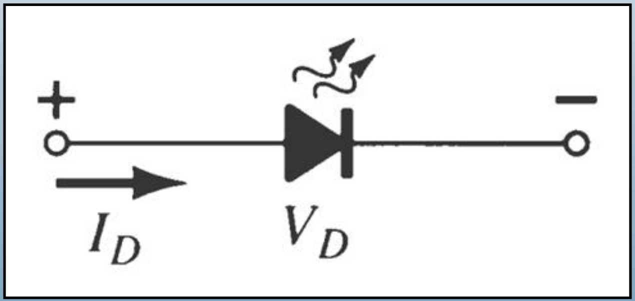
- Typical specifications for a 10-V, 500-mW, 20% Zener diode
- Expected to vary as 10 V + 20%, or from 8 V to 12 V.
- Both 10% and 50% diodes are also readily available.



Zener Voltage Nominal V_Z (V)	Test Current I_{ZT} (mA)	Maximum Dynamic Impedance Z_{ZT} at I_{ZT} (Ω)	Maximum Knee Impedance Z_{ZK} at I_{ZK} (Ω)	(mA)	Maximum Reverse Current I_R at V_R (µA)	Test Voltage V_R (V)	Maximum Regulator Current I_{ZM} (mA)	Typical Temperature Coefficient (%/°C)
10	12.5	8.5	700	0.25	10	7.2	32	+0.072

Light-Emitting Diode (LED)

An **LED** emits light when it is forward biased, which can be in the infrared or visible spectrum.



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

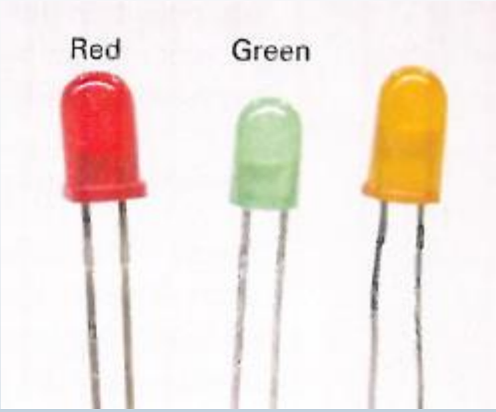
Light-Emitting Diodes

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

Causes of Light in LEDs

- In a forward-biased LED, free electrons cross the junction and fall into holes
  - As these electrons fall from a higher to a lower energy level, they radiate energy
  - In an LED, the energy is radiated as light
  - The color of the light depends on the bandgap of the diode material

Color Spectrum of Light-Emitting Diodes (LED)



Light-Emitting Diodes

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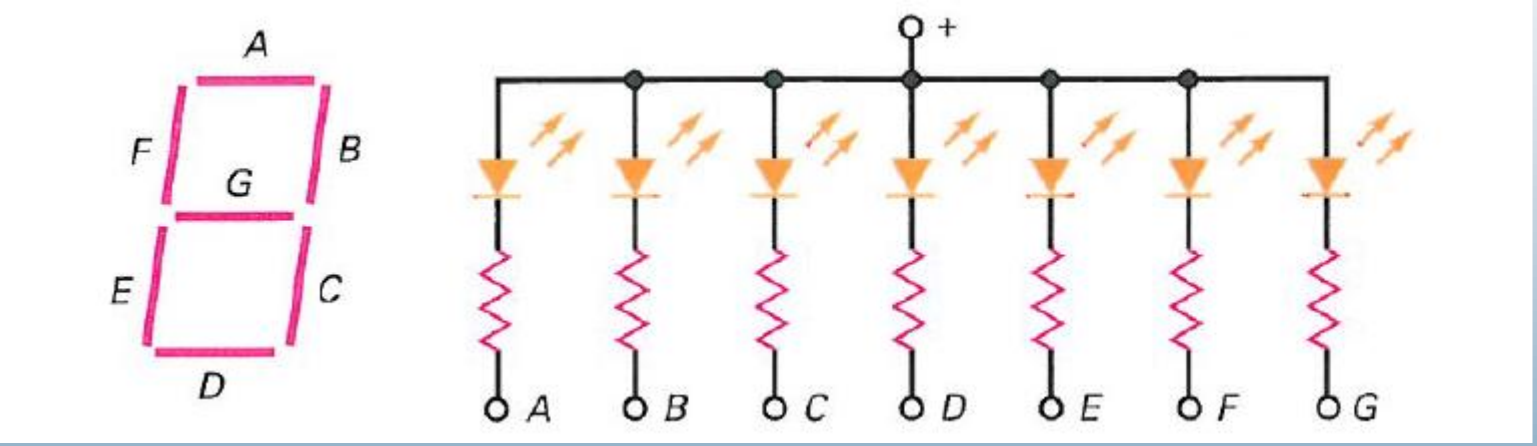
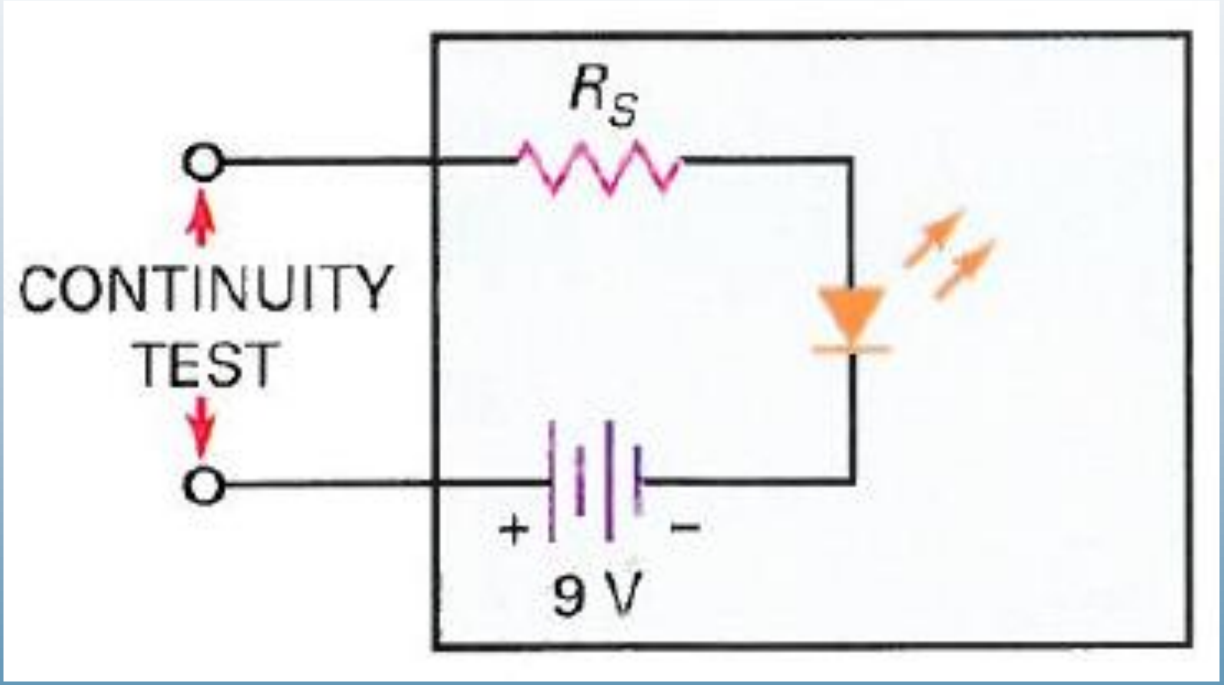
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

- **LEDs that produce visible radiation are useful with instruments, calculators, and so on**
- **LEDs have replaced incandescent lamps in many applications because of their low voltage, long life, and fast on-off switching**
- **The infrared LED finds applications in burglar alarm systems, remote controls, CD players, and other devices requiring invisible radiation**

Seven-Segment Display



Continuity Tester



Resistance Levels

Semiconductors react differently to DC and AC currents.

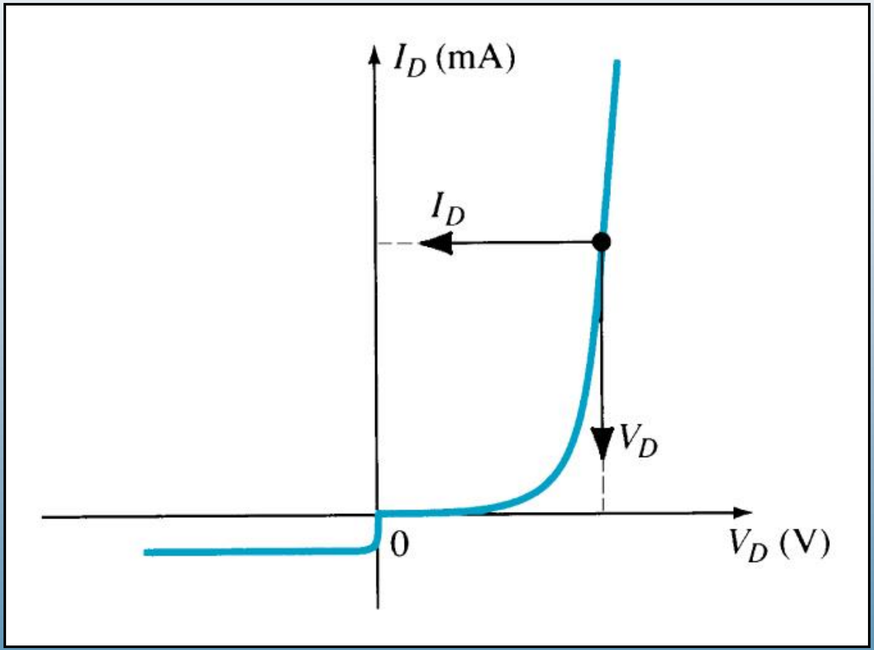
There are three types of resistance:

- **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)

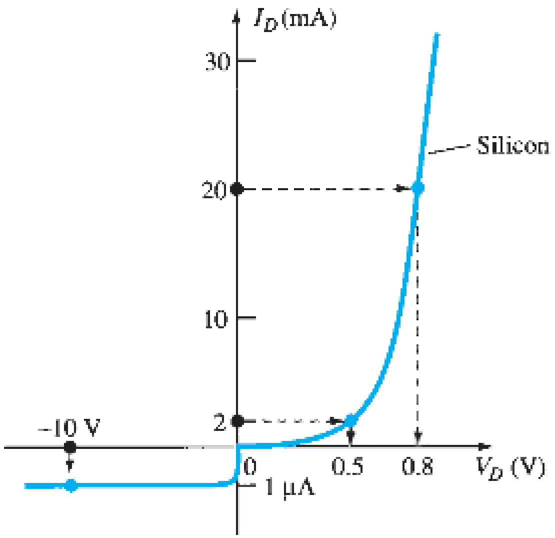


FIG. 1.24
Example 1.3.

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

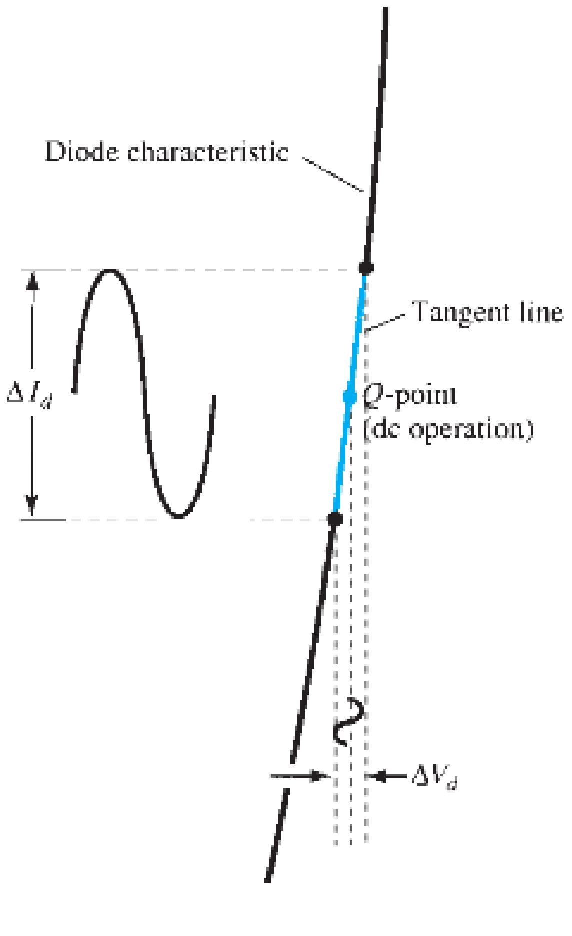


FIG. 1.25
Defining the dynamic or ac resistance.

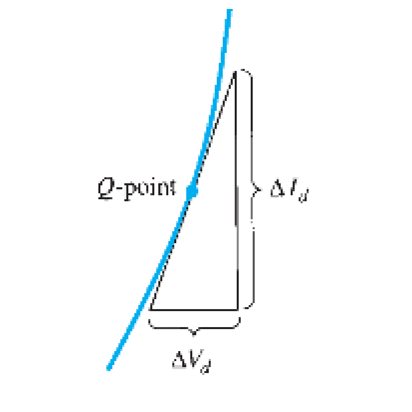


FIG. 1.26
Determining the ac resistance at a Q-point.

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

In the forward bias region: $$r_d = \frac{26\,\mathrm{mV}}{I_D}$$

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.

Total AC (Dynamic) Resistance

The total ac resistance r'_d includes r_B, *which is 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).*

$$r'_d = r_d + r_B = \frac{V_T}{I_D} + r_B = \frac{26\,\text{mV}}{I_D} + r_B$$

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:

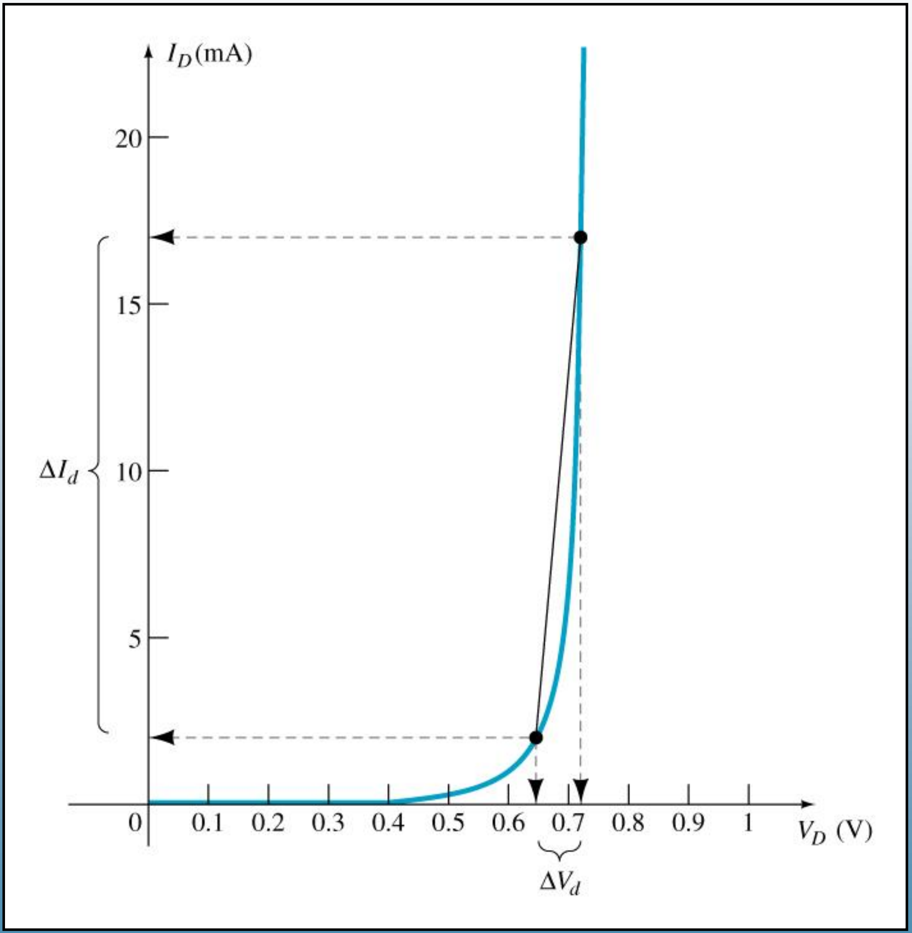
$$\mathrm{r}'_{\mathrm{d}} = \infty$$

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

Average AC Resistance

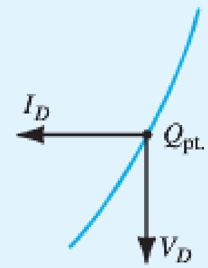
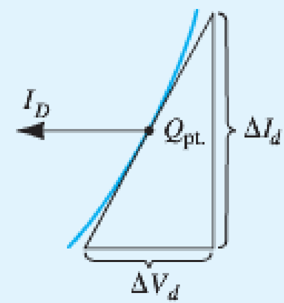
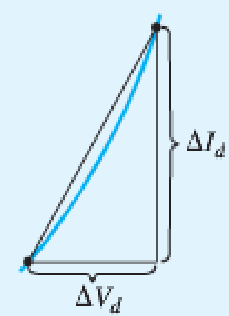
$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \bigg|\ pt.\,to\,pt.$$

AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.

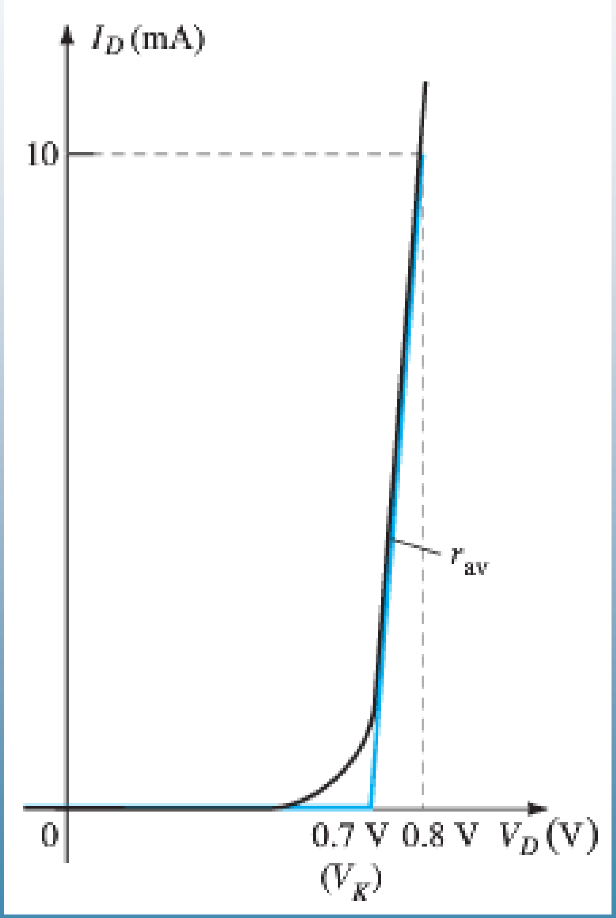


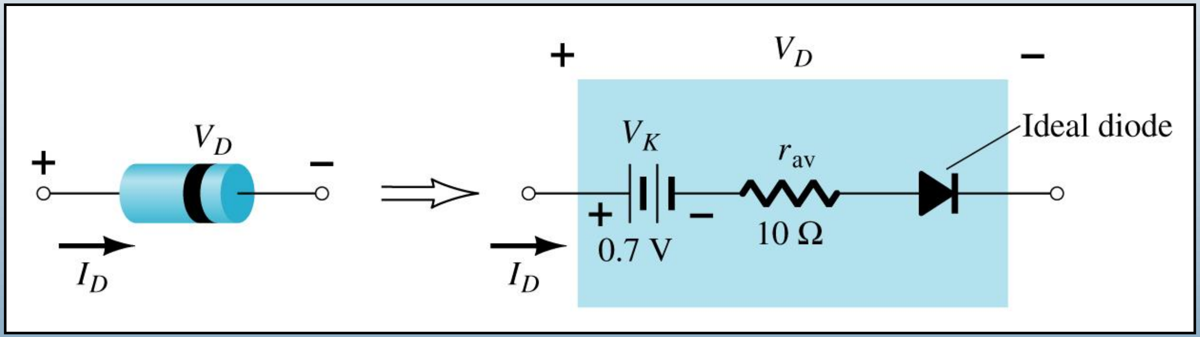
Summary Table

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

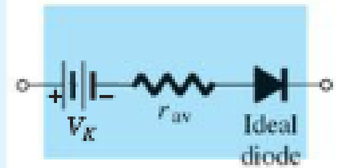
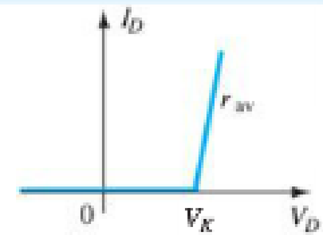
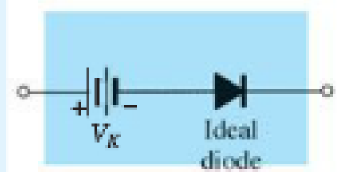
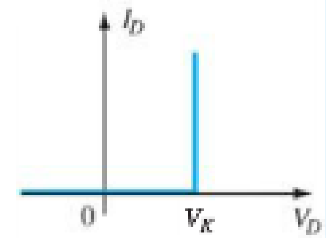
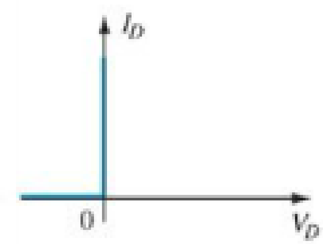
Diode Equivalent Circuit





Summary Table

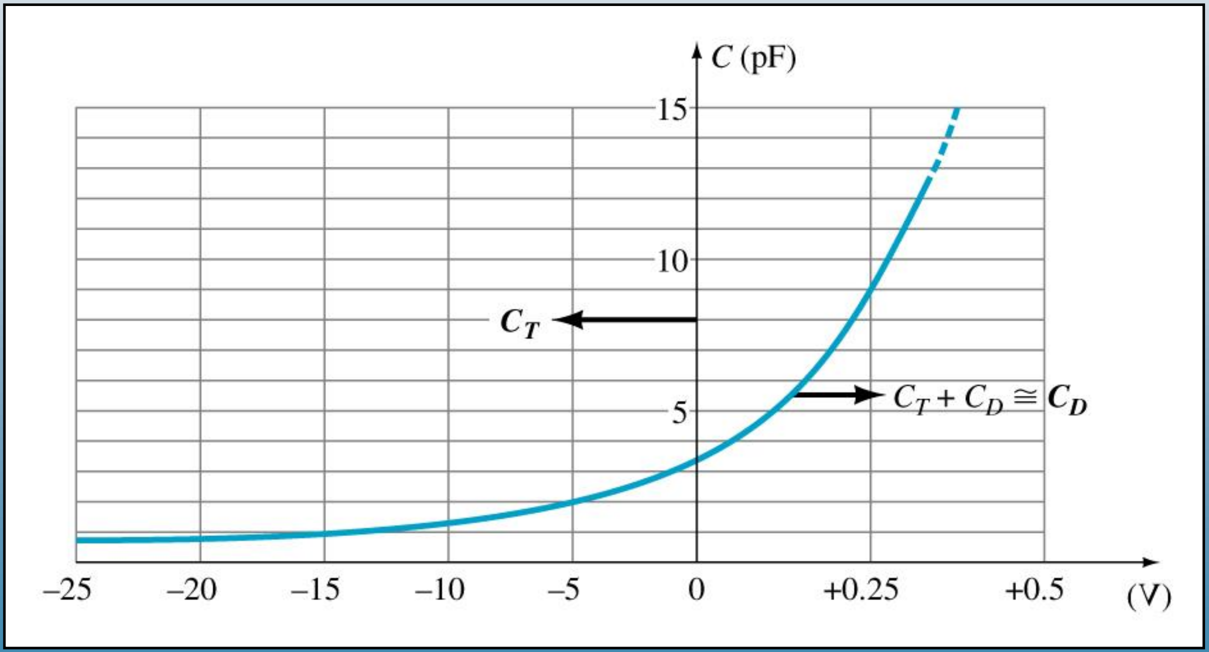
Diode Equivalent Circuits (Models)

Type	Conditions	Model	Characteristics
Piecewise-linear model 3rd Approximation			
Simplified model 2nd Approximation	$R_{network} \gg r_{av}$		
Ideal device 1st Approximation	$R_{network} \gg r_{av}$ $E_{network} \gg V_K$		

Diode Capacitance

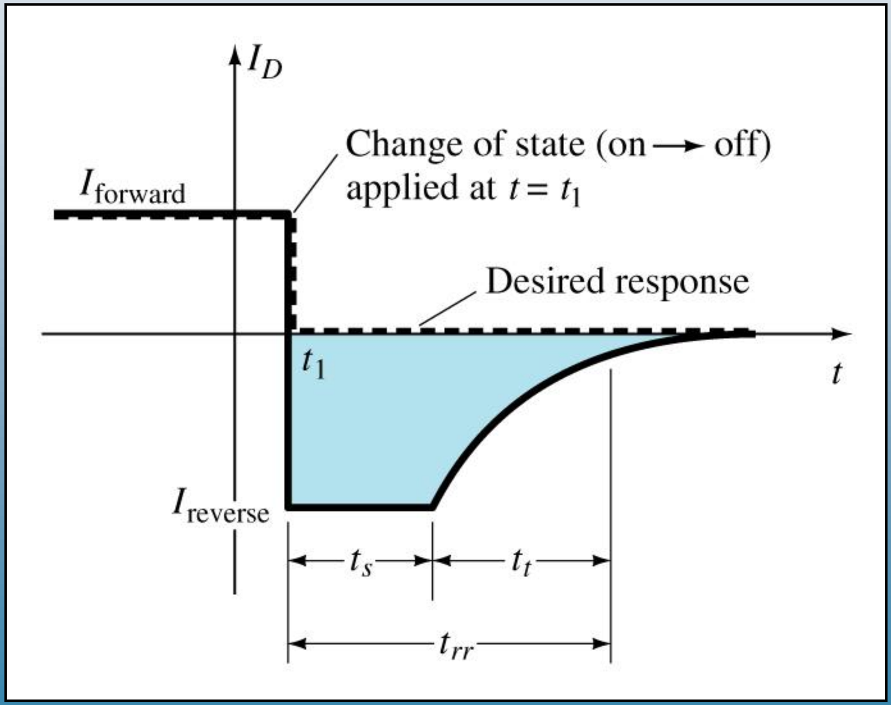
When ***reverse biased***, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance (C_T). The amount of capacitance depends on the reverse voltage applied.

When ***forward biased***, storage capacitance or diffusion capacitance (C_D) exists as the diode voltage increases.



Reverse Recovery Time (t_{rr})

Reverse recovery time *is the time required for a diode to stop conducting when switched from forward bias to reverse bias.*



Diode Specification Sheets

Diode data sheets contain standard information, making cross-matching of diodes for replacement or design easier.

1. Forward Voltage (V_F) at a specified current and temperature
2. Maximum forward current (I_F) at a specified temperature
3. Reverse saturation current (I_R) at a specified voltage and temperature
4. Reverse voltage rating, PIV or PRV or $V_{(BR)}$, at a specified temperature
5. Maximum power dissipation at a specified temperature
6. Capacitance levels
7. Reverse recovery time, t_{rr}
8. Operating temperature range