Lecture 1
Electronics 1

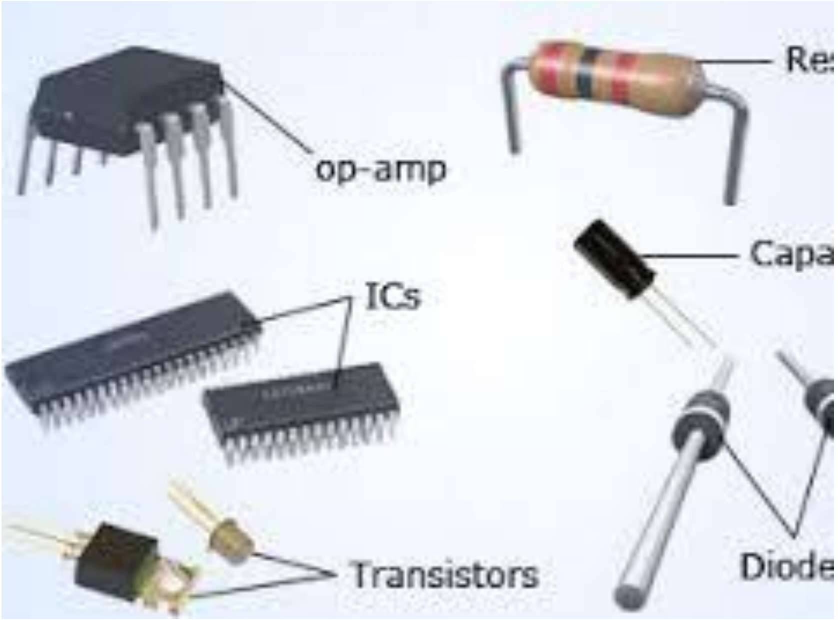
Electronics (1)

Lecture 1

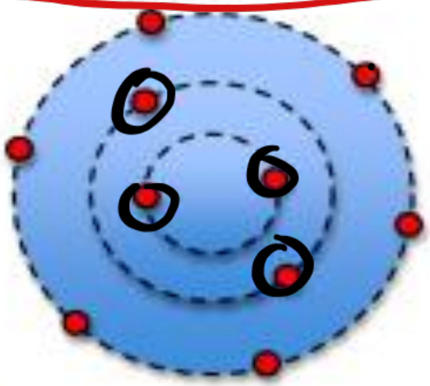
Dr. Shaeen Kalathil

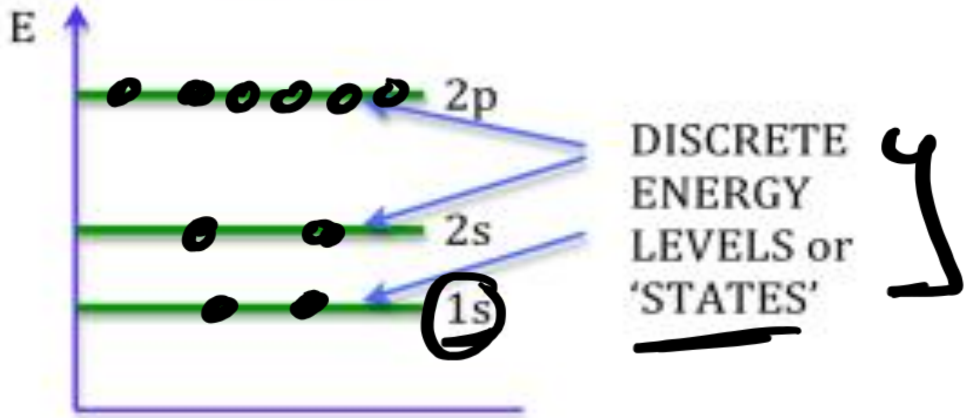
Semiconductor

The word Electronics is derived from electron mechanics which means the study of the behavior of electrons under different conditions of externally applied fields.

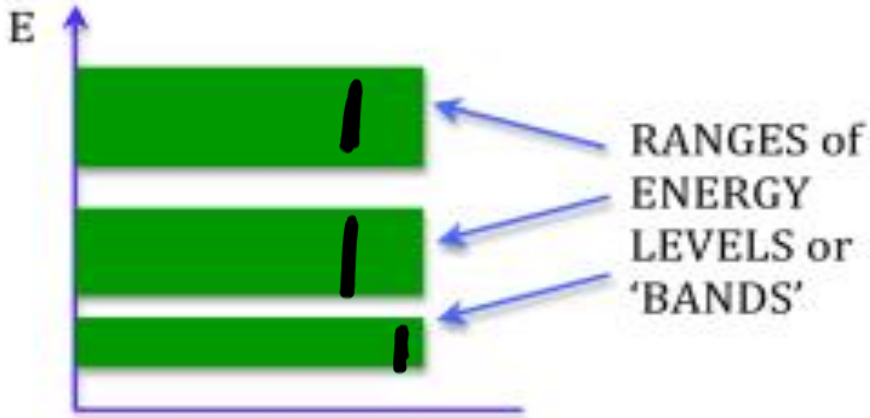


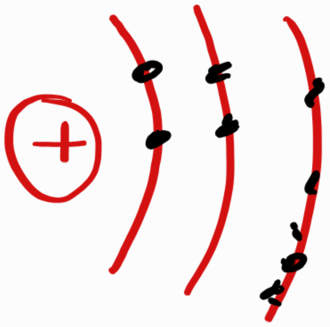
INDIVIDUAL ATOM





CRYSTALLINE SOLID - 10^{23} ATOMS (only 24 atoms drawn here)

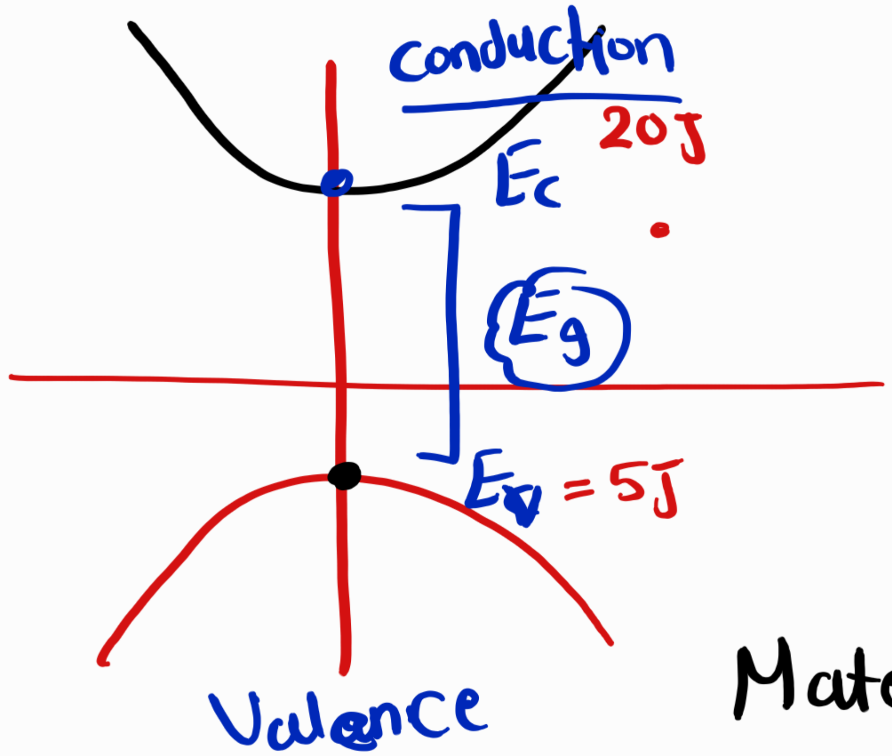


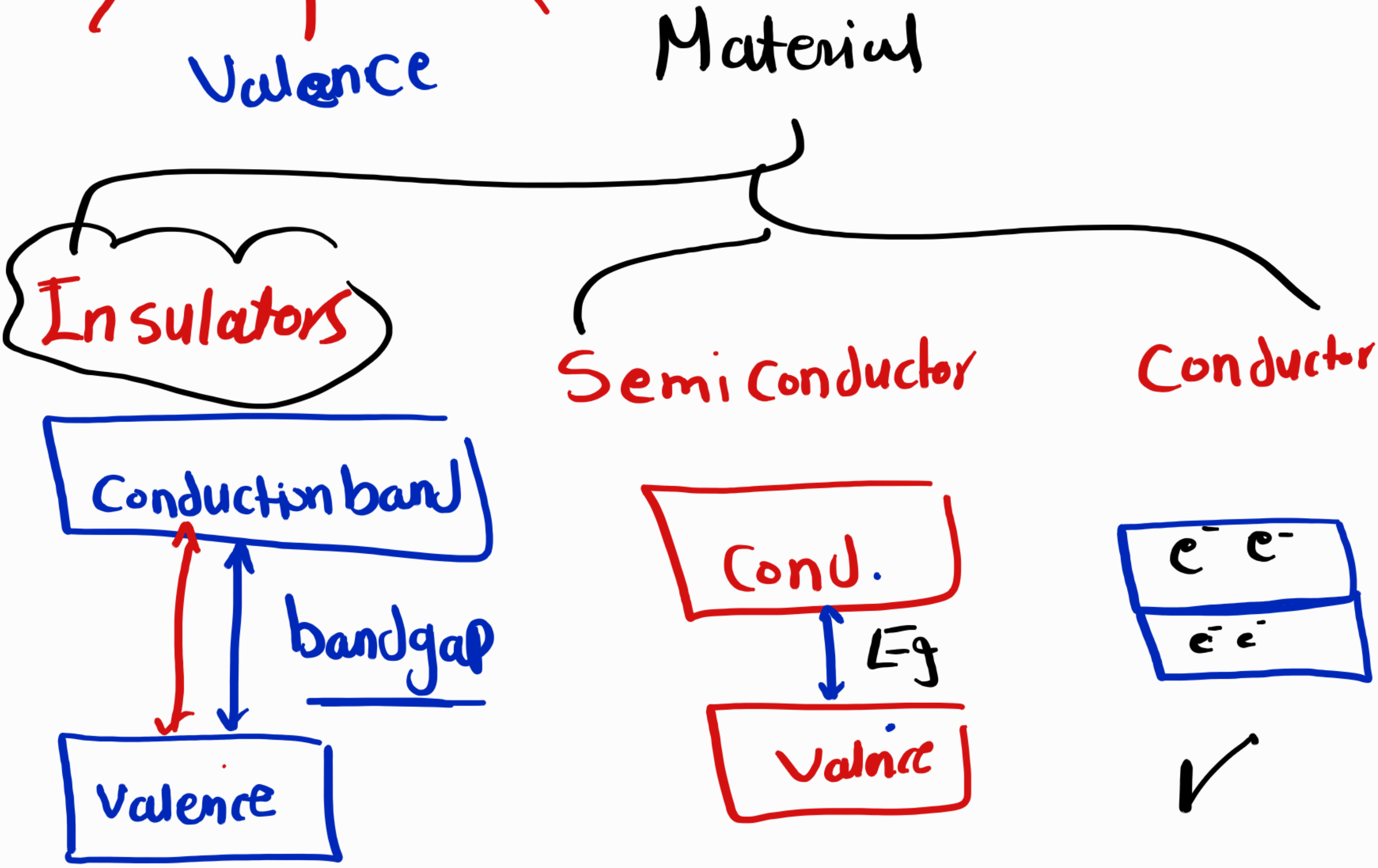


$1s^2 2s^2 2p^6 3s^2 3p^6$

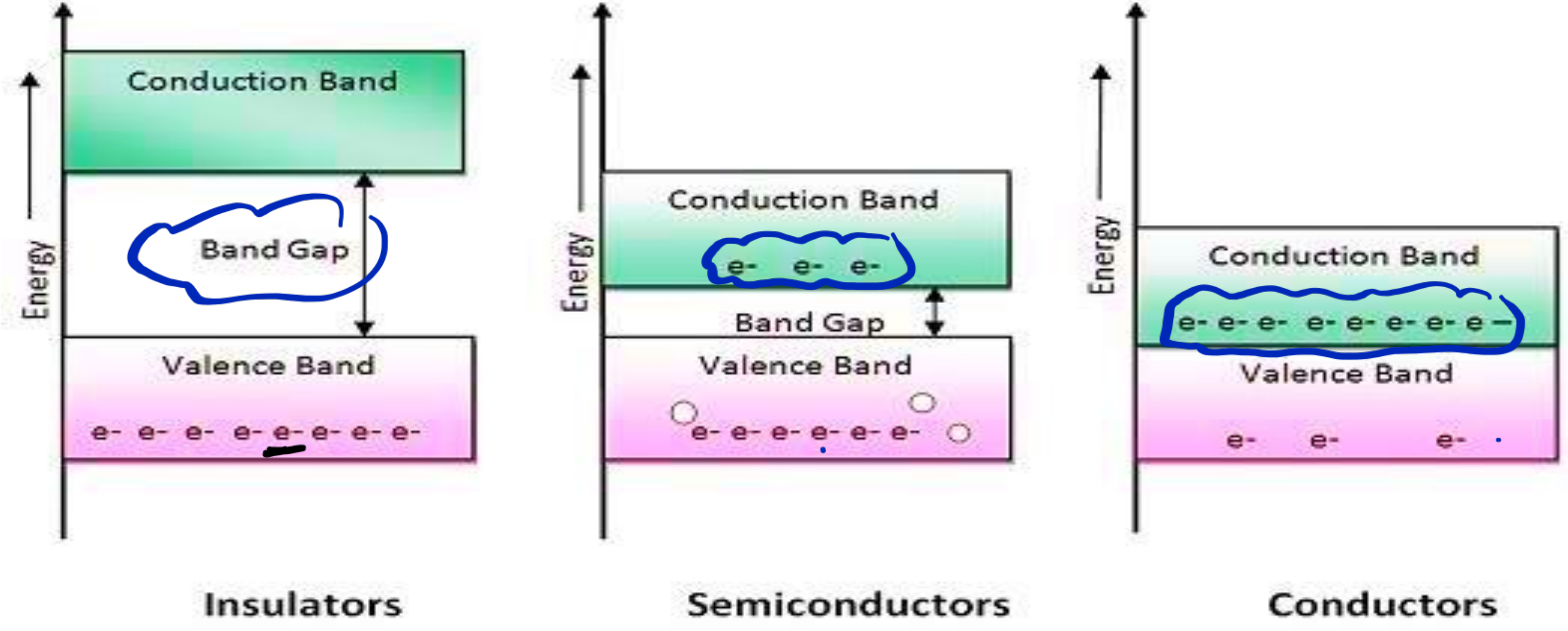
n=1

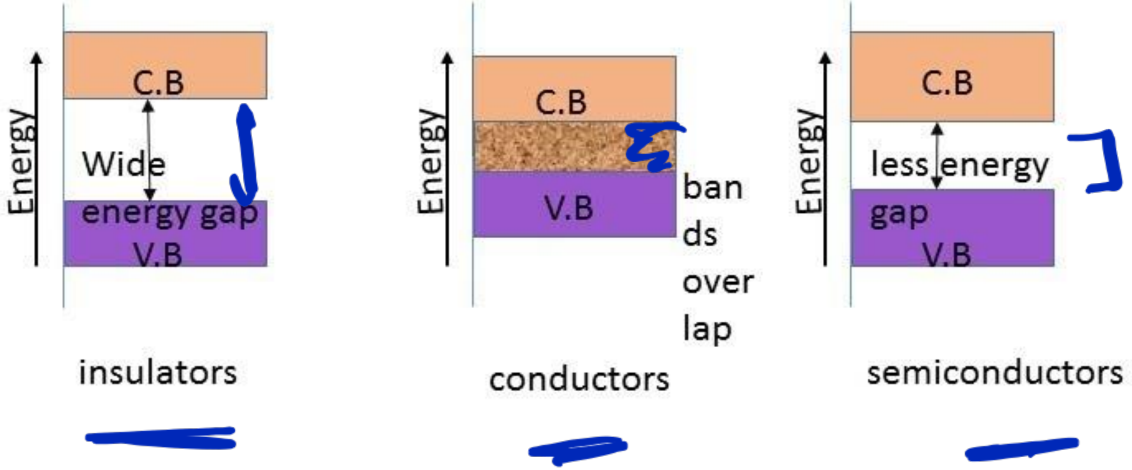
n

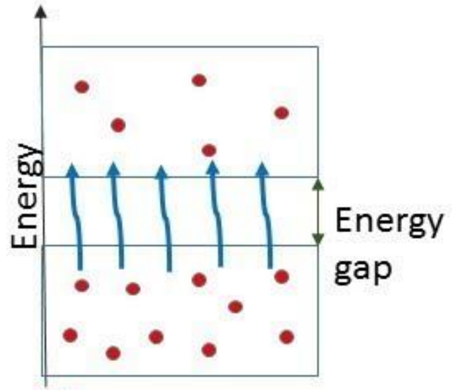




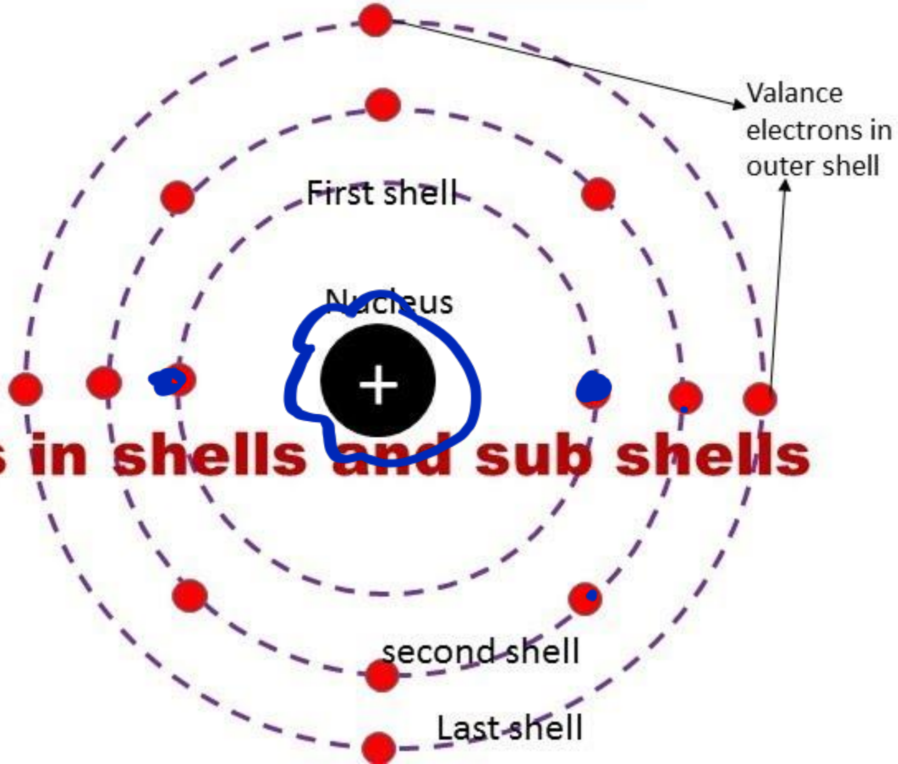
Based on the energy band structure, solids are classified as insulators, semiconductors and metals.







Energy band theory



Distribution of electrons in shells and sub shells

Band Theory of Solids

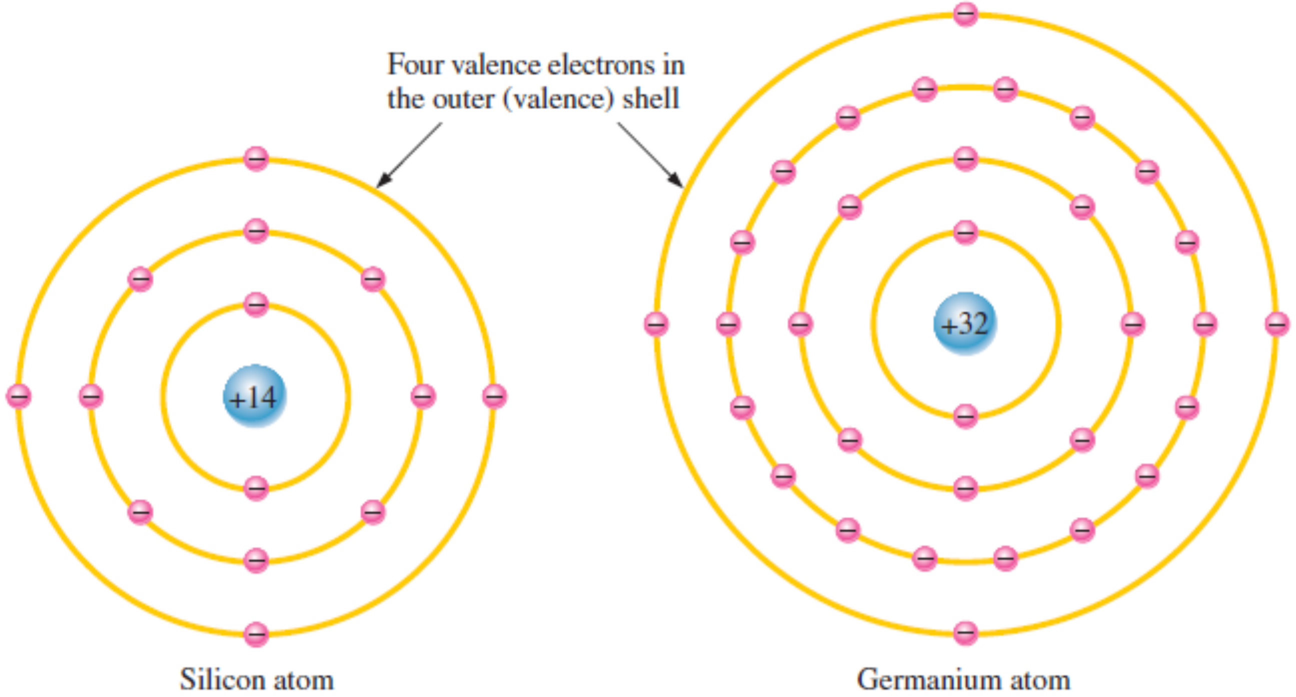
A useful way to visualize the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies as in the case of free atoms, the available energy states form bands.

In insulators the electrons in the valence band are separated by a large gap from the conduction band, in conductors like metals the valence band overlaps the conduction band, and in semiconductors there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap. With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically.

- Examples of insulators are rubber, plastics, glass, mica, and quartz.
- Examples of conductors are copper (Cu), silver (Ag), gold (Au), and aluminum (Al).

Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

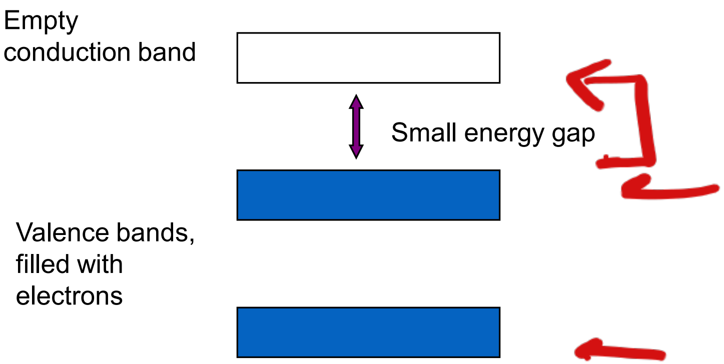
Ex : Silicon and Germanium



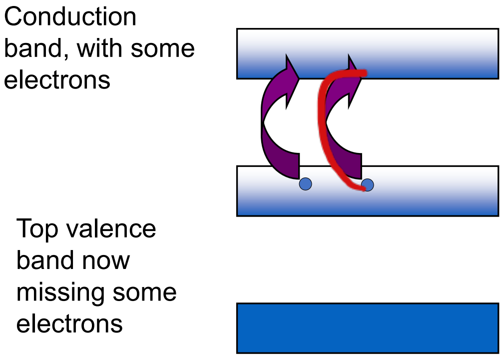
Semiconductors:

- Some materials have a filled valence band just like insulators but a small gap to the conduction band.

  At zero Kelvin the material behave just like an insulator but at room temperature, it is possible for some electrons to acquire the energy to jump up to the conduction band. The electrons move easily through this conduction band under the application of an electric field. This is an intrinsic semiconductor.

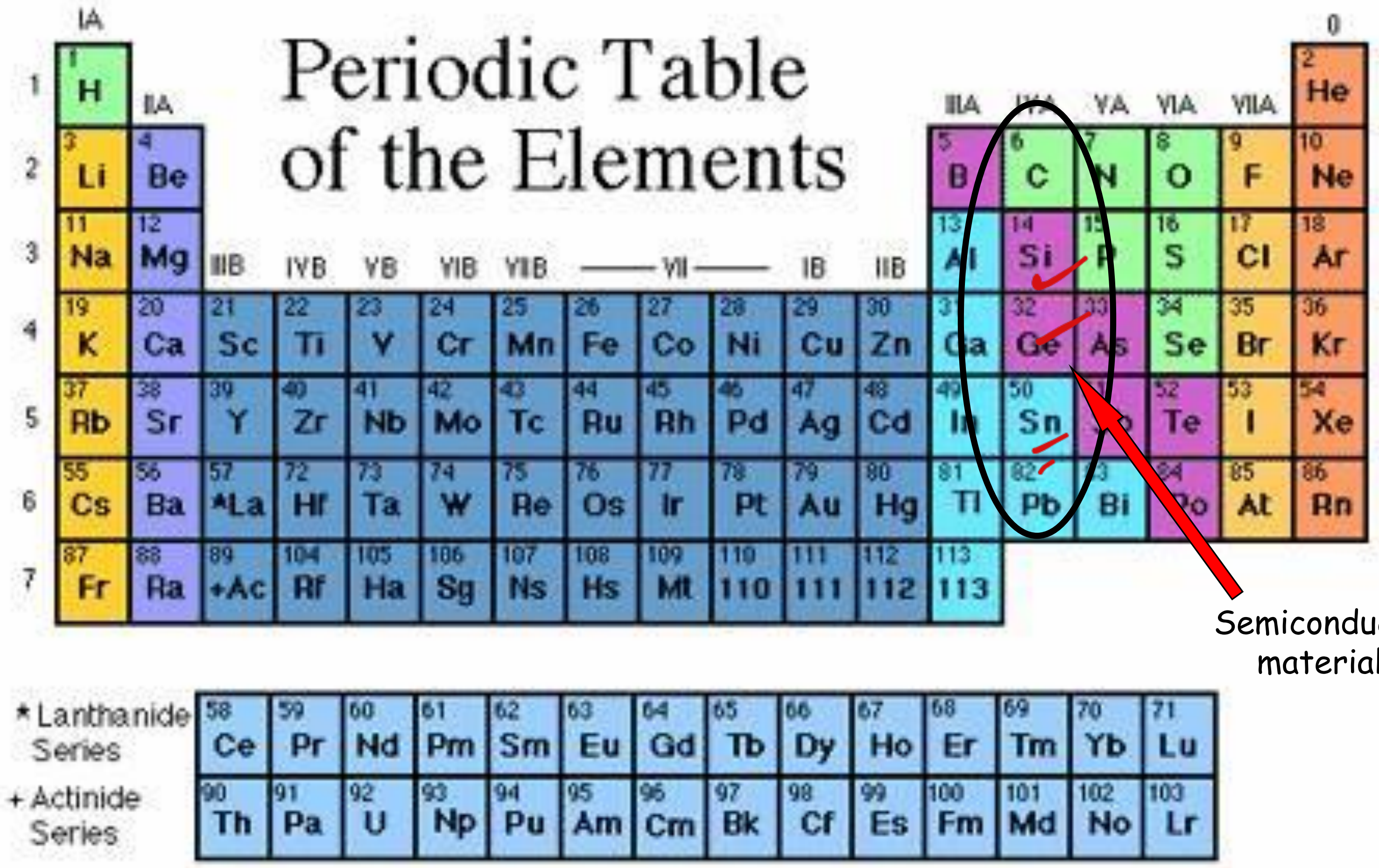


At zero Kelvin – no conduction



At room temperature – some conduction

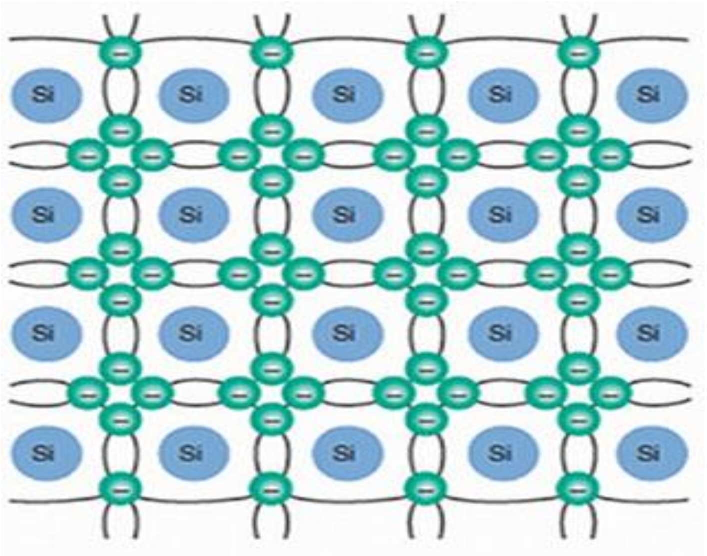
So where are all these materials to be found in the periodic table ?



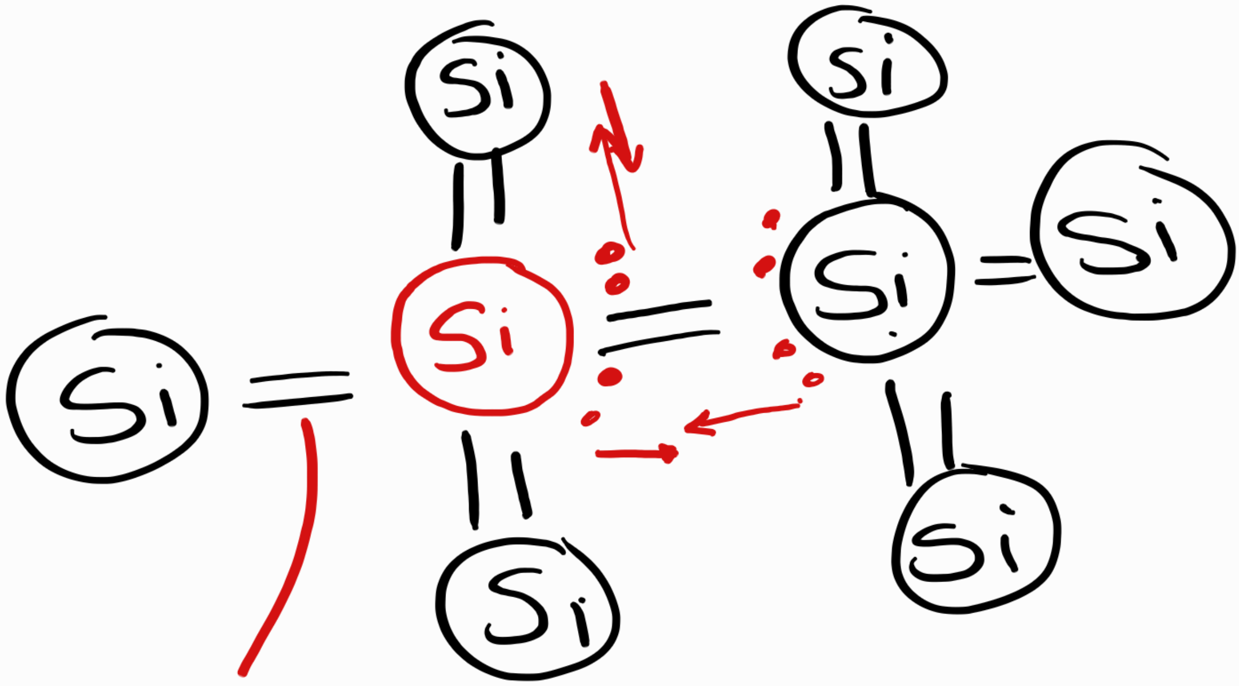
Semiconductor materials

The Silicon Atom

In the case of Silicon, each of the 4 outer electrons enters into a covalent bond with a neighbouring atom.

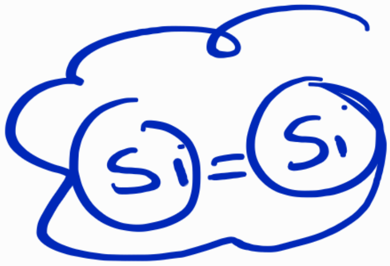


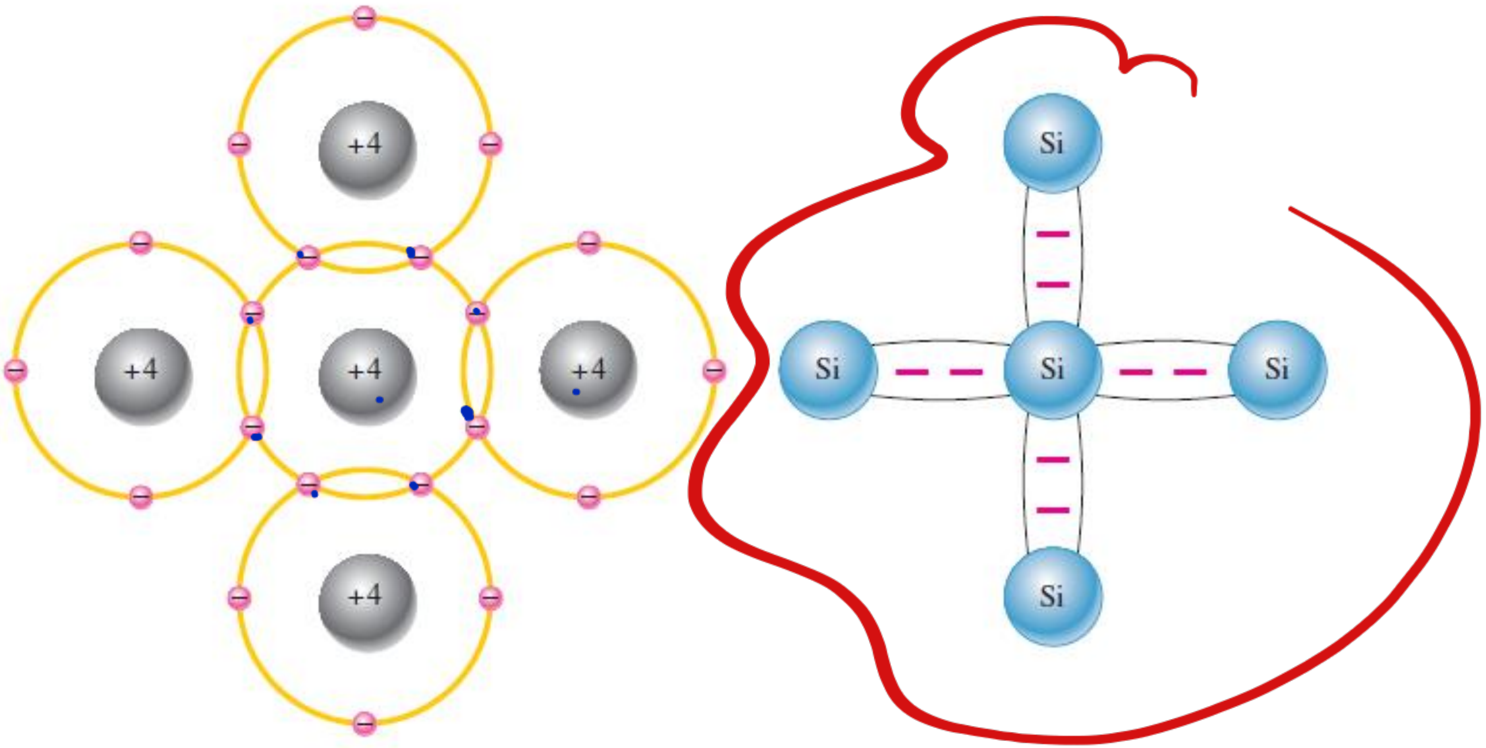
A Covalent Bond Formed by the Sharing of Electrons in an Outer Energy Level



Covalent bond

- Ionic bond
  - $Na^{+}Cl^{-}$
- Metalic
  - Fe^{+2}
- Covalent





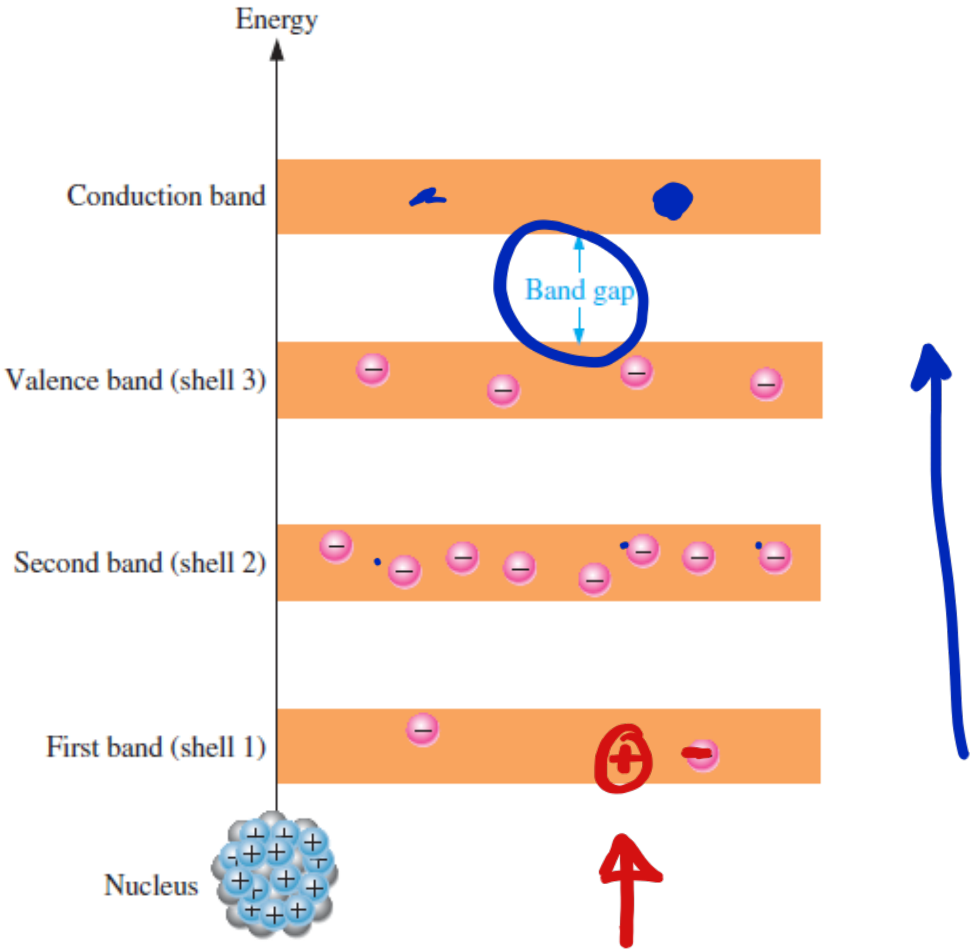
(a) The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.

(b) Bonding diagram. The red negative signs represent the shared valence electrons.

FIGURE 1–12

Energy band diagram for an unexcited atom in a pure (intrinsic) silicon crystal. There are no electrons in the conduction band.

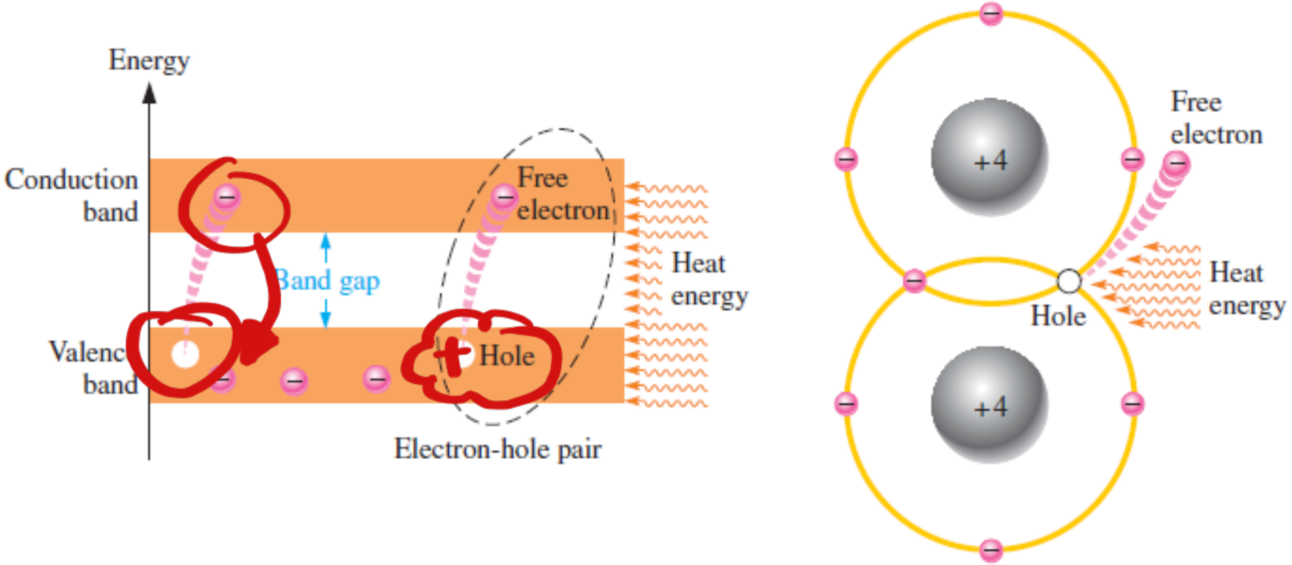
At zero Kelvin



A hole is created when an electron breaks its covalent bond.

▶ FIGURE 1–13

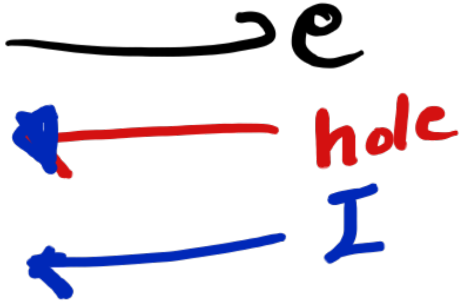
Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free electrons.

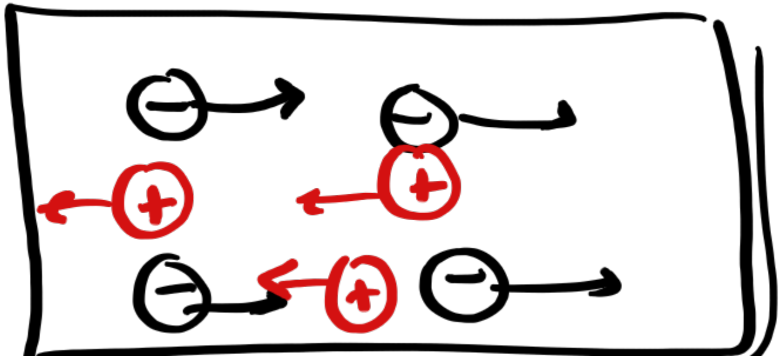


(a) Energy diagram

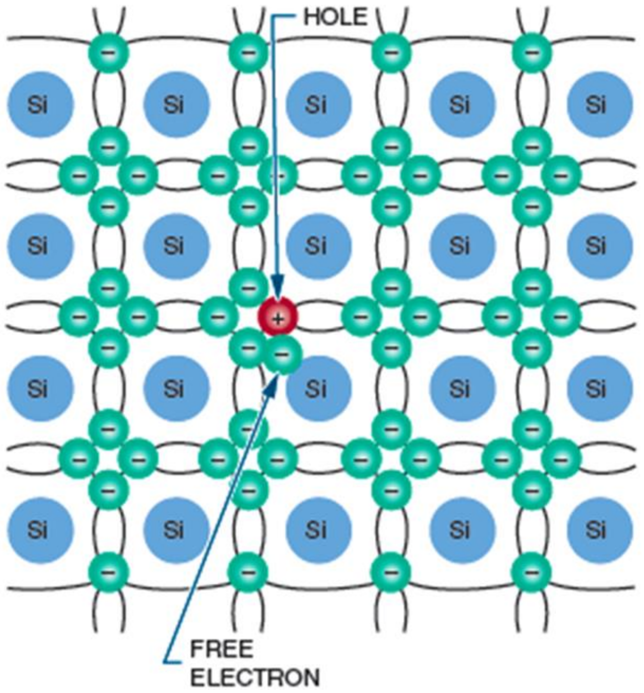
(b) Bonding diagram

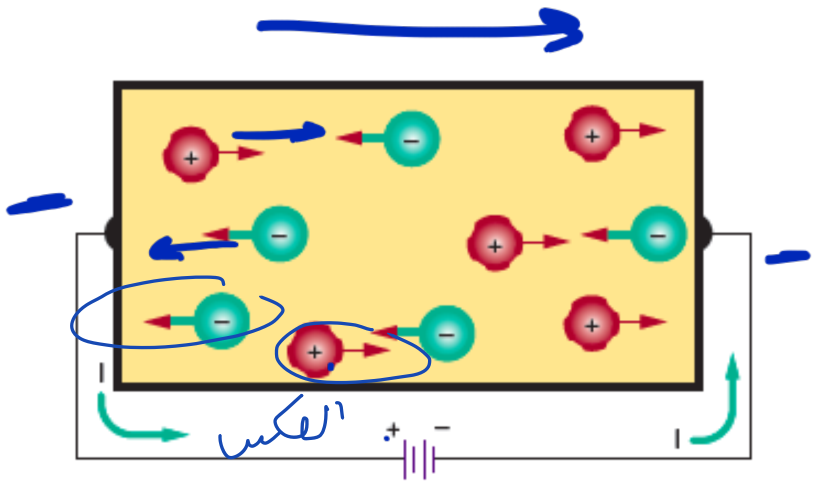
When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair**. **Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.





Current flow in pure semiconductor material.





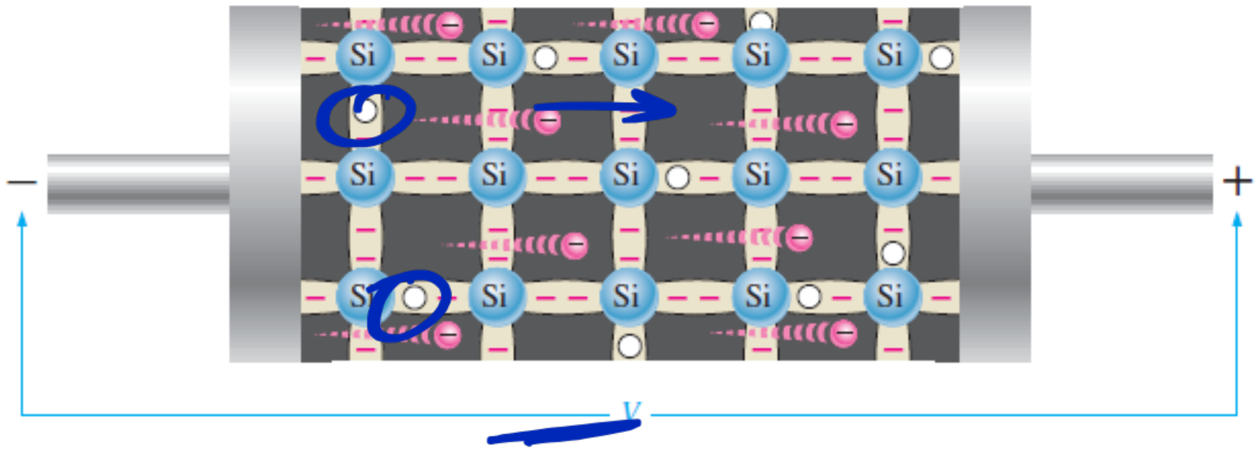


FIGURE 1–15

Electron current in intrinsic silicon is produced by the movement of thermally generated free electrons.

Si Ge

Holes and Intrinsic Semiconductors

- When electrons move into the conduction band, they leave behind vacancies in the valence band. These vacancies are called **holes**. Because holes represent the absence of negative charges, it is useful to think of them as **positive charges.**

- A semiconductor in which there is a balance between the number of electrons in the conduction band and the number of holes in the valence band is called an **intrinsic semiconductor.**

Examples of intrinsic semiconductors include pure Silicon and germanium.

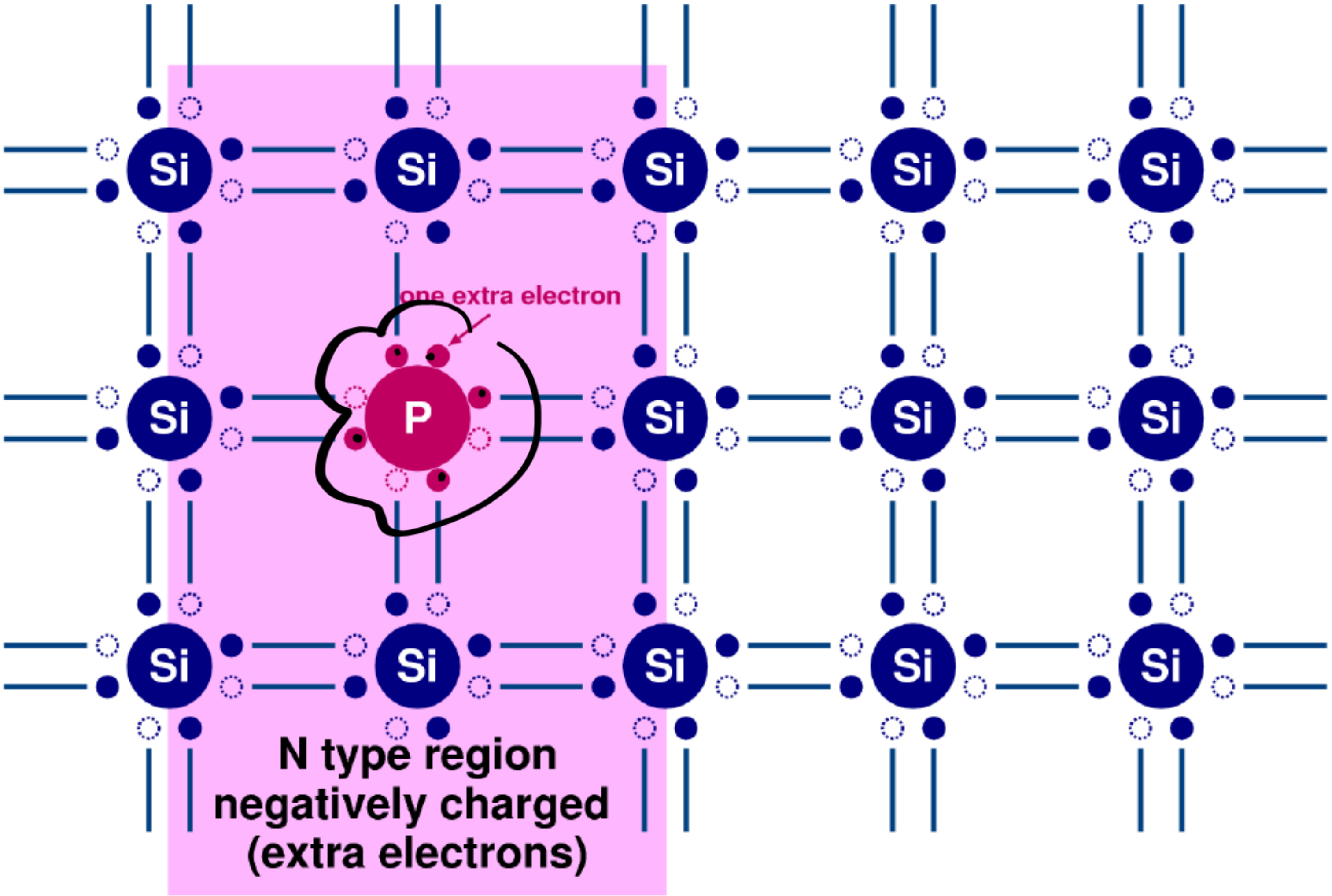
N-Type — P-Type

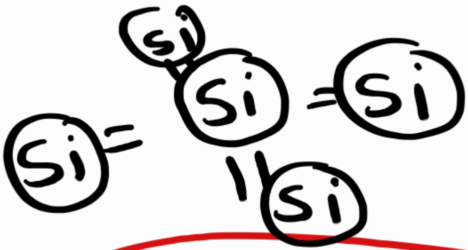
Since semiconductors are generally poor conductors, their conductivity can be drastically increased by the controlled addition of impurities to the intrinsic (pure) semiconductive material. This process, called **doping**, increases the number of current carriers (electrons or holes). The two categories of impurities are *n*-type and *p*-type.

N-Type Semiconductor

To increase the number of conduction-band electrons in intrinsic silicon, **pentavalent** impurity atoms are added. These are atoms with five valence electrons such as arsenic (As), phosphorus (P), bismuth (Bi), and antimony (Sb).

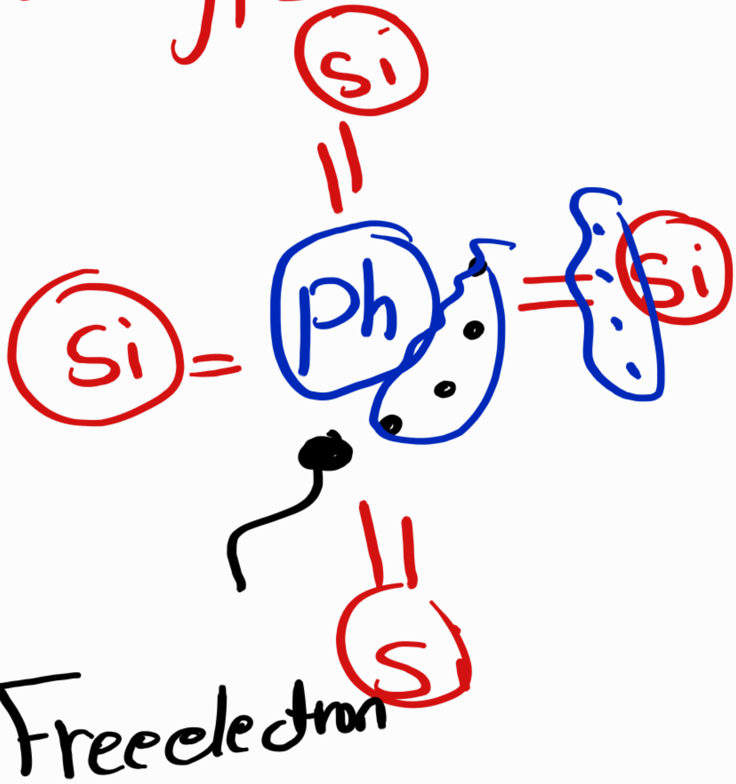
N-type Doping





Doping

N-Type



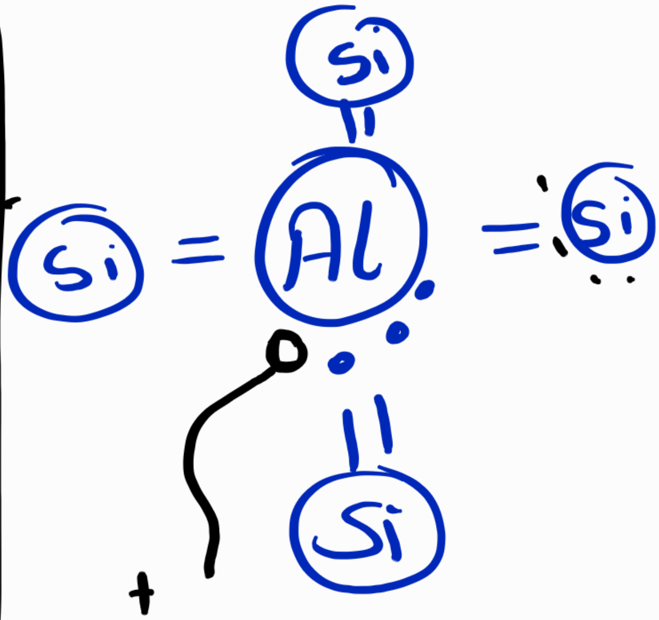
Majority = electron (−)

Minority = hole (+)

N-Type

negative

P-Type



Majority = hole

Minority = electron

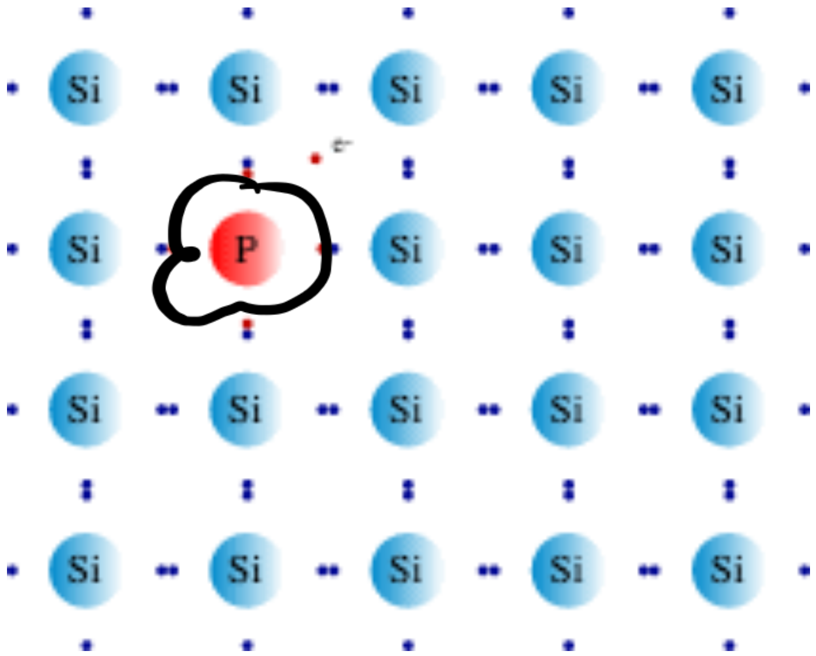
P-Type

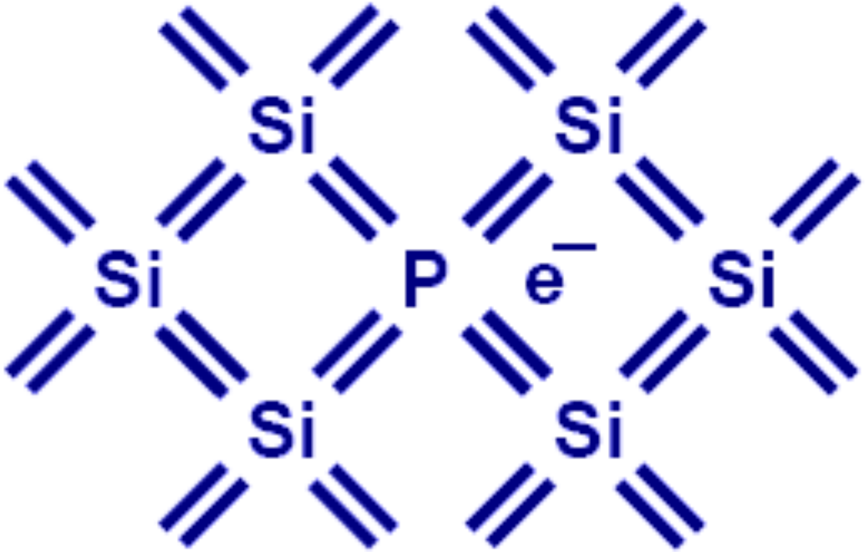
→ Positive (+)

hole

Doping (N type)

- Semiconductors can be "doped" with other elements to change its electrical properties.
- For example, if Si is doped with pentavalent atom (atoms with five valence electrons) each atom can contribute a conduction electron, so that the Si lattice has more electrons than holes, *i.e.* it becomes "N type":





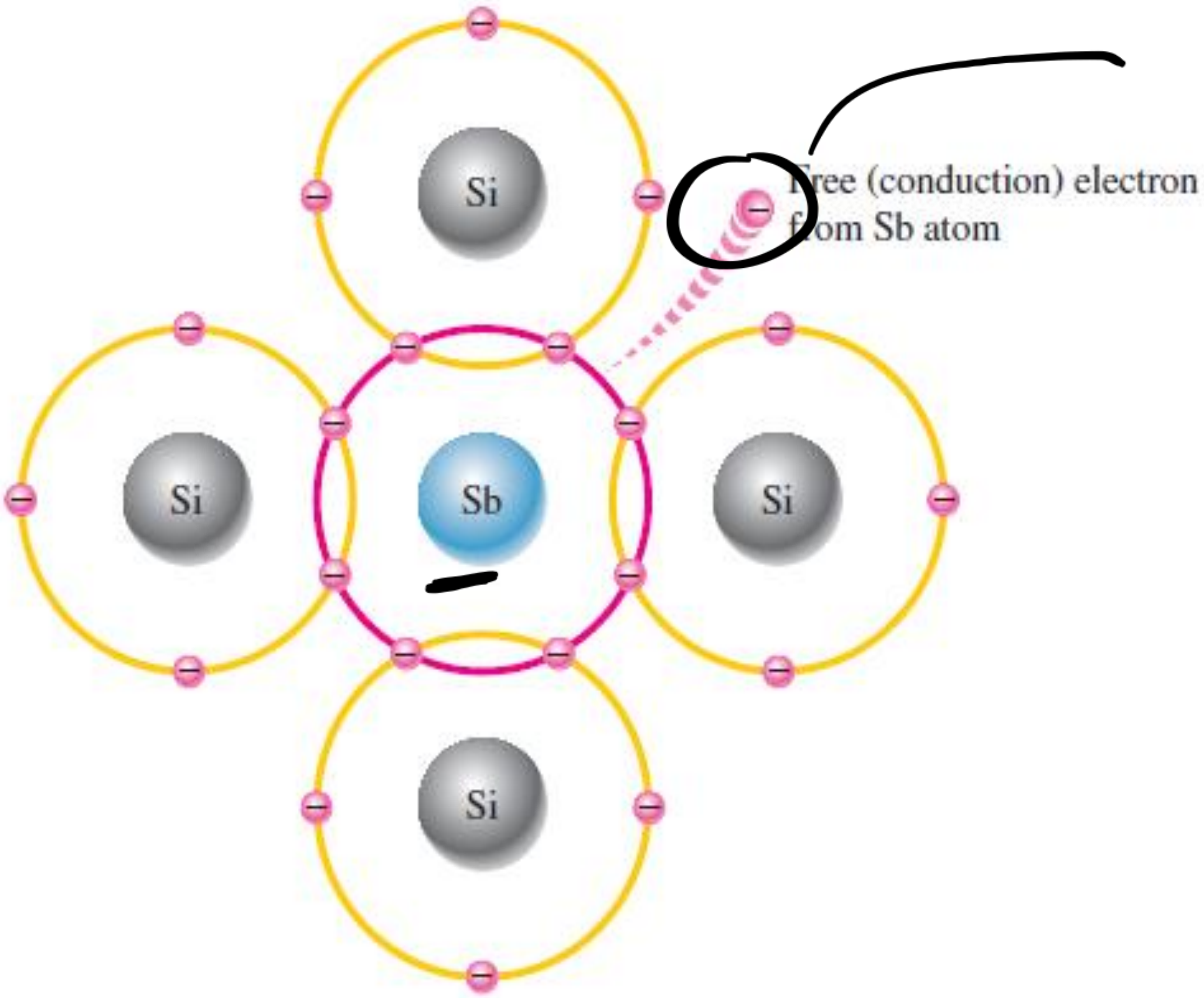
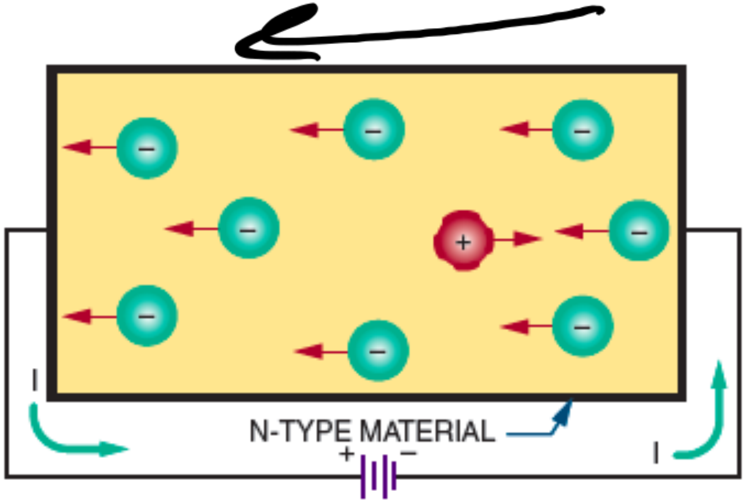


FIGURE 1–17

Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

Current flow in N-type material



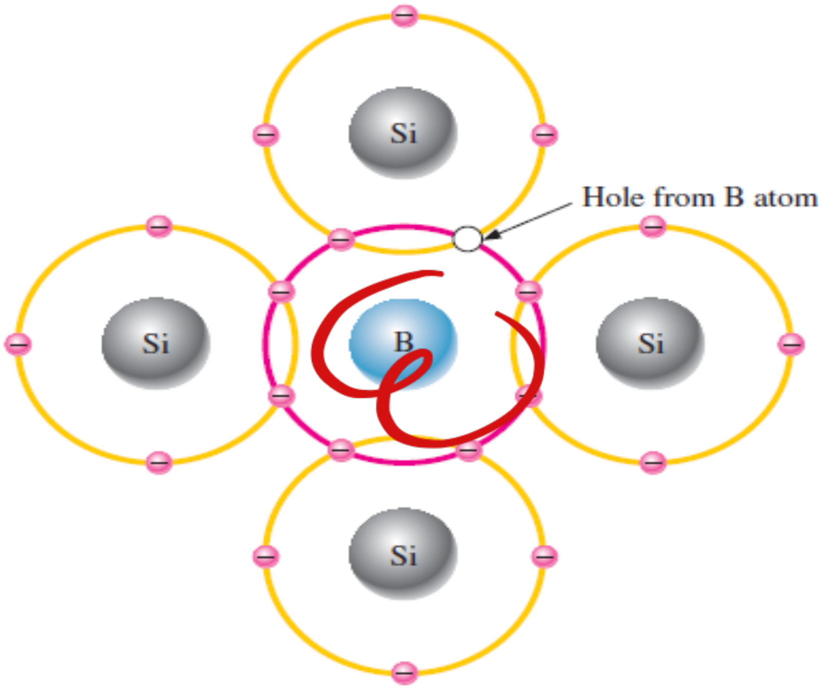
Majority and Minority Carriers Since most of the current carriers are electrons, silicon (or germanium) doped with pentavalent atoms is an *n*-type semiconductor (the *n* stands for the negative charge on an electron). The electrons are called the **majority carriers** in *n*-type material. Although the majority of current carriers in *n*-type material are electrons, there are also a few holes that are created when electron-hole pairs are thermally generated. These holes are *not* produced by the addition of the pentavalent impurity atoms. Holes in an *n*-type material are called **minority carriers.**

P-Type Semiconductor

To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added. These are atoms with three valence electrons such as boron (B), indium (In), and gallium (Ga).

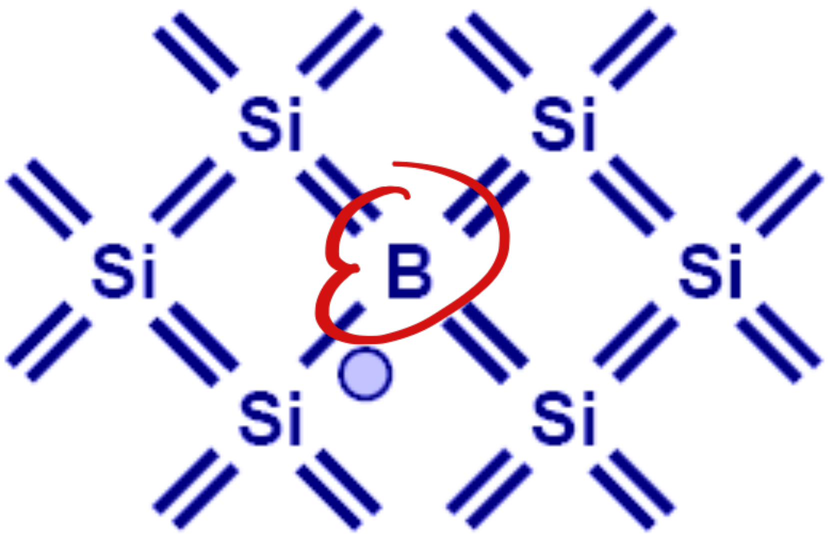
▶ FIGURE 1–18

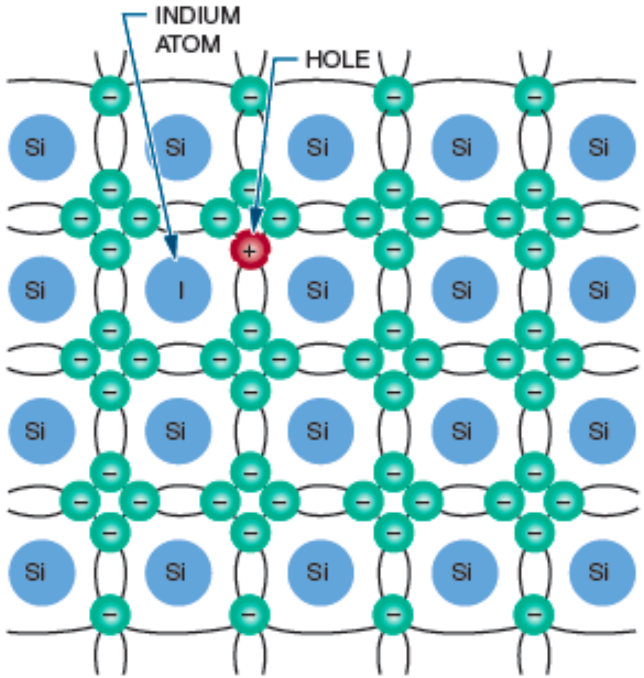
Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.



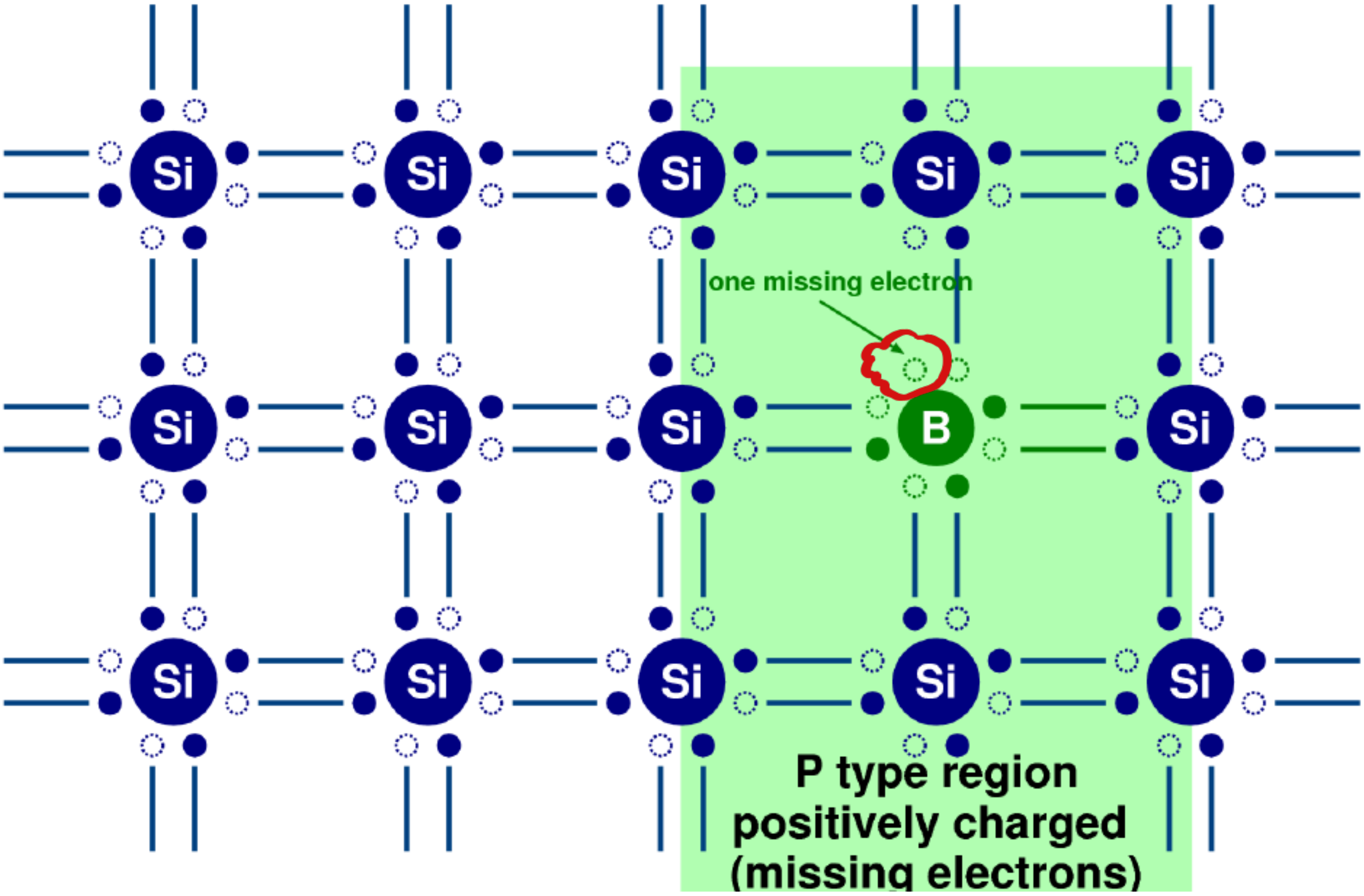
Doping (P type)

- If Si is doped with trivalent, each atom can contribute a hole, so that the Si lattice has more holes than electrons, *i.e.* it becomes “P type”:

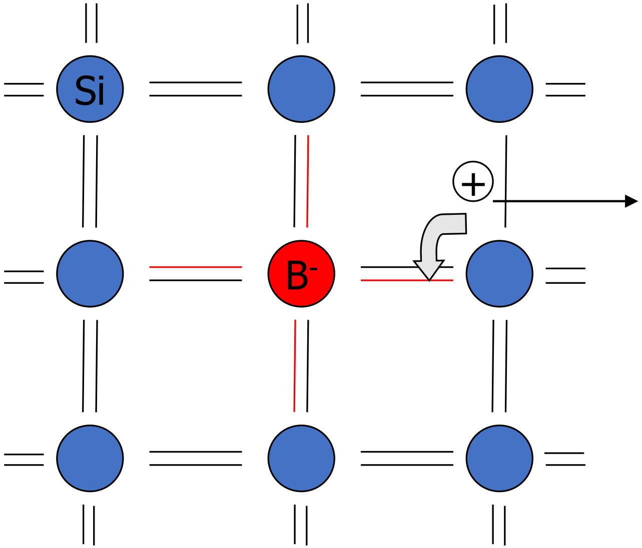


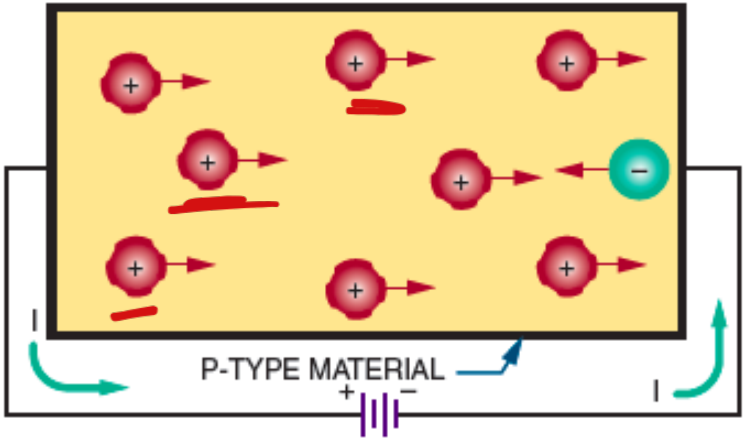


P-type Doping



p-type doping in silicon

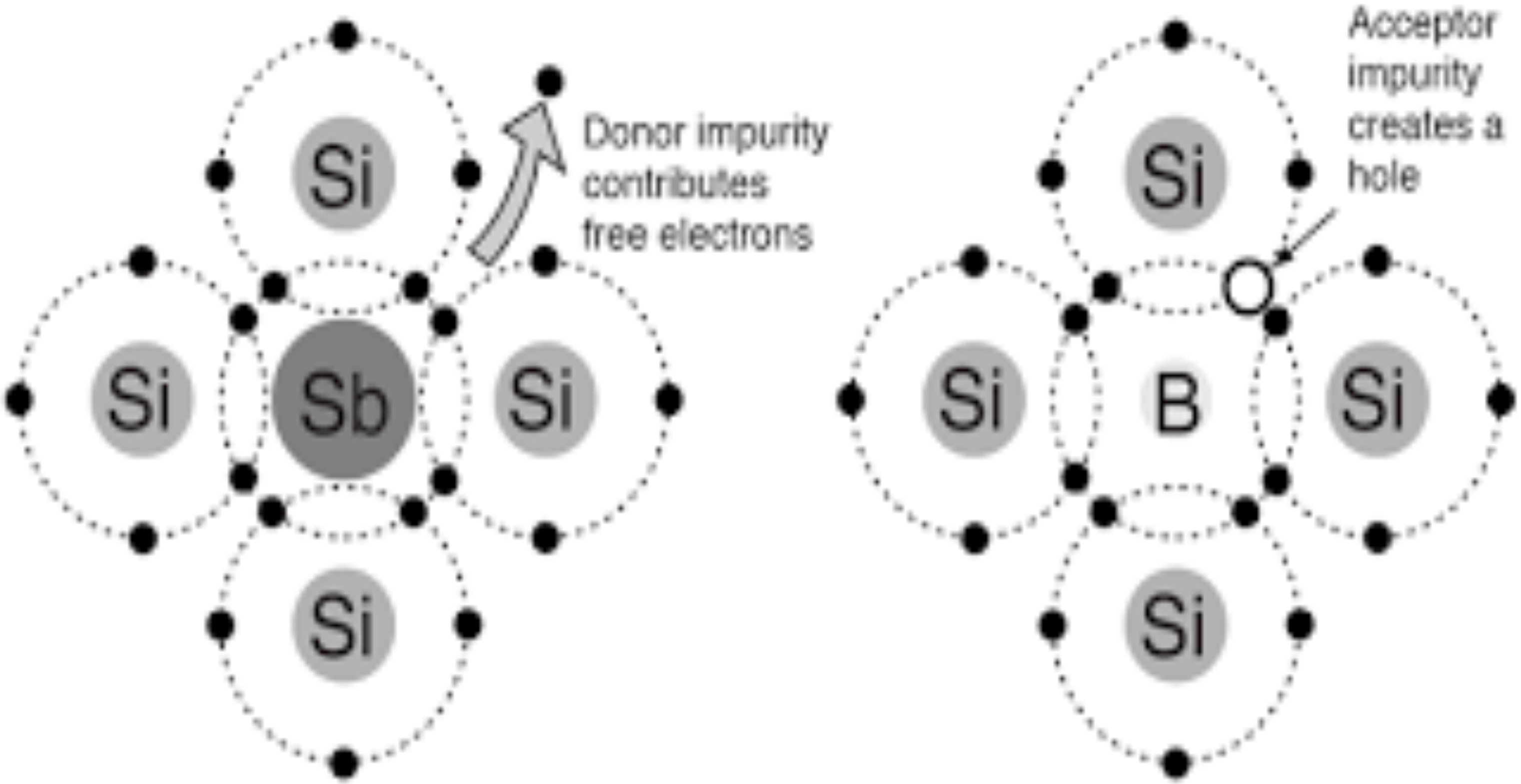




What are P-type and N-type ?

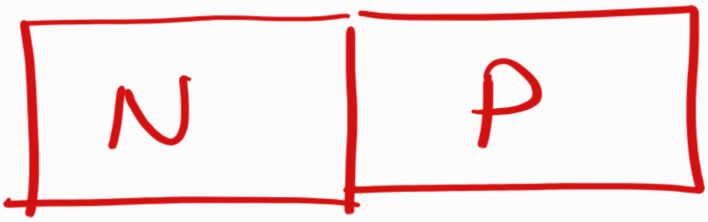
- Semiconductors are classified into P-type and N-type semiconductor
- P-type: A P-type material is one in which holes are majority carriers and electrons minority carriers.
- N-type: A N-type material is one in which electrons are majority charge carriers and holes are minority charge carriers.

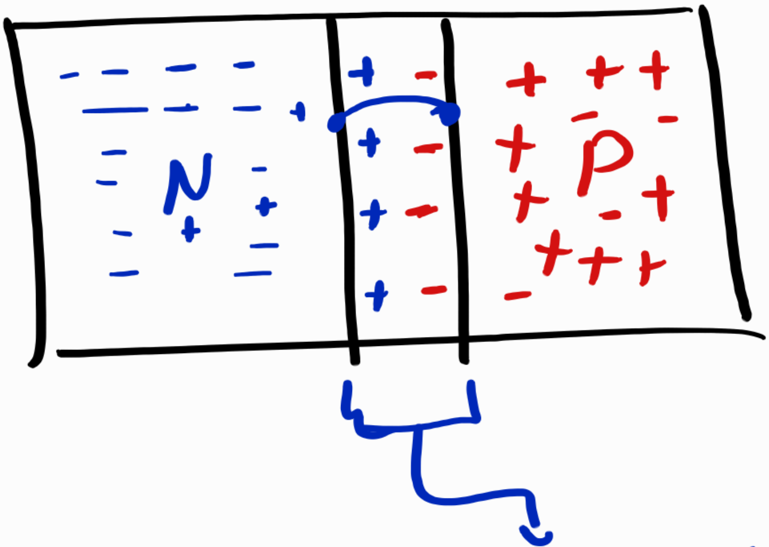
Extrinsic Semiconductors



What Is So Great About Semiconductors?

- You can "engineer" its properties
  - Make it **P type** by injecting type-III elements (B, Ga, In)
  - Make it **N type** by injecting elements from type-V (P,As)
- Starting with a pure semiconductor, you can combine P and N regions next to each other
- Allows you to make interesting electrical devices
  - Diodes
  - Transistors





depletion region

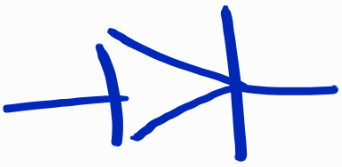
⇒ V_0

Si

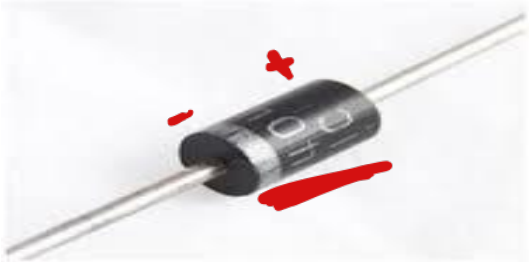
0.7v

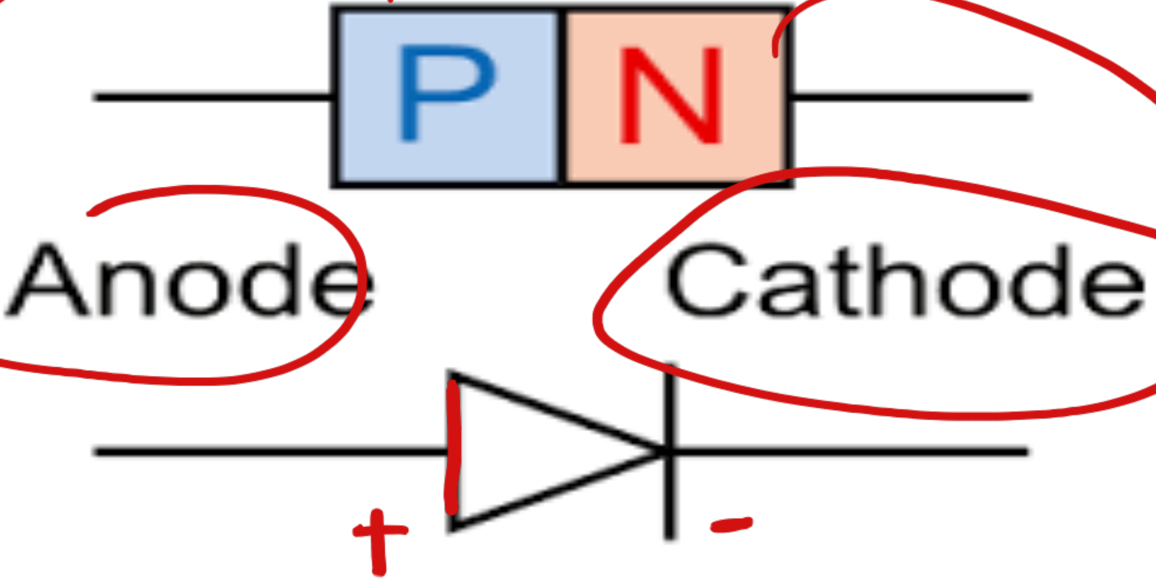
Ge

0.3v

<u>Diode</u> 

PN JUNCTION DIODE





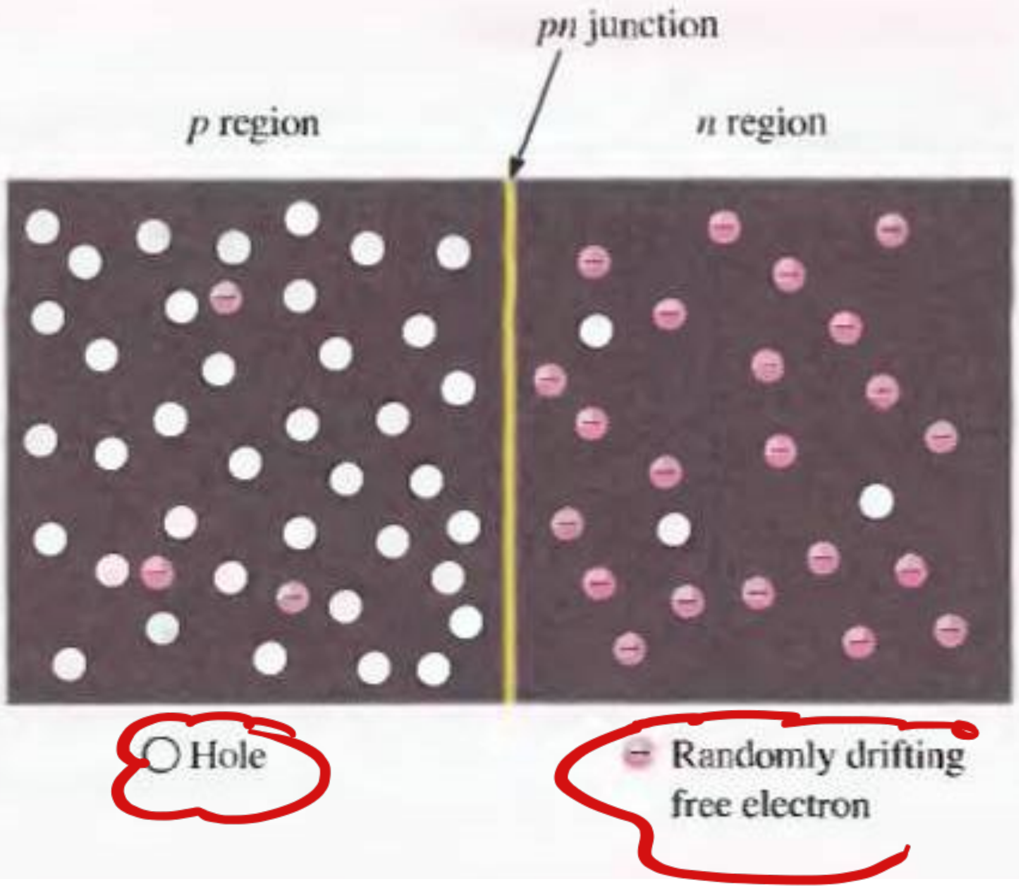
What is P – N junction semiconductor and how is it formed?

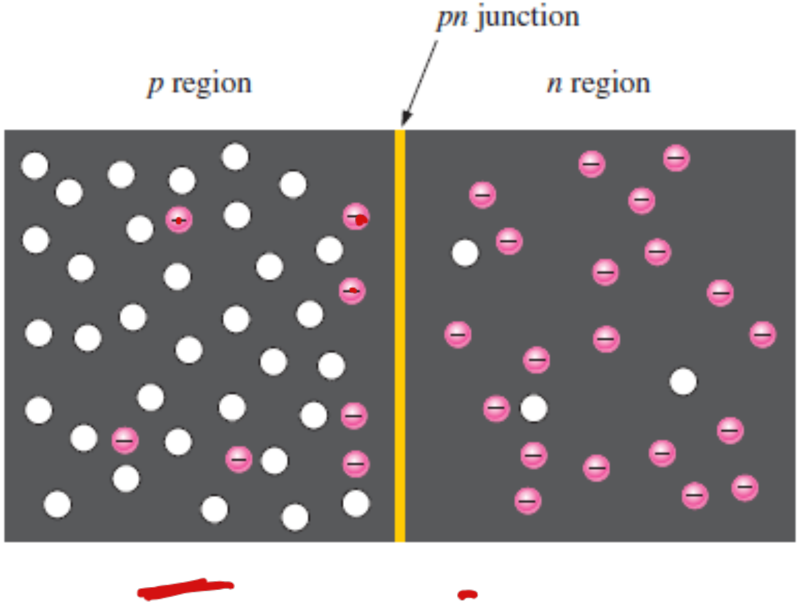
It's a combination of P type semiconductor with N type semiconductor to achieve the practical utility of both.

It's formed, when a P type semi conductor is joined to a N type semiconductor.

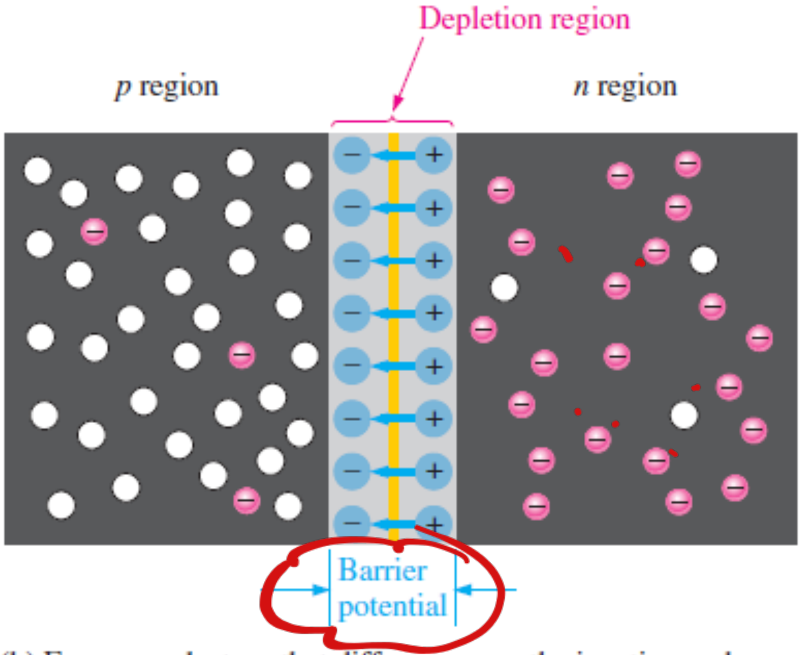
FIGURE 1–17

The basic diode structure at the instant of junction formation showing only the majority and minority carriers.

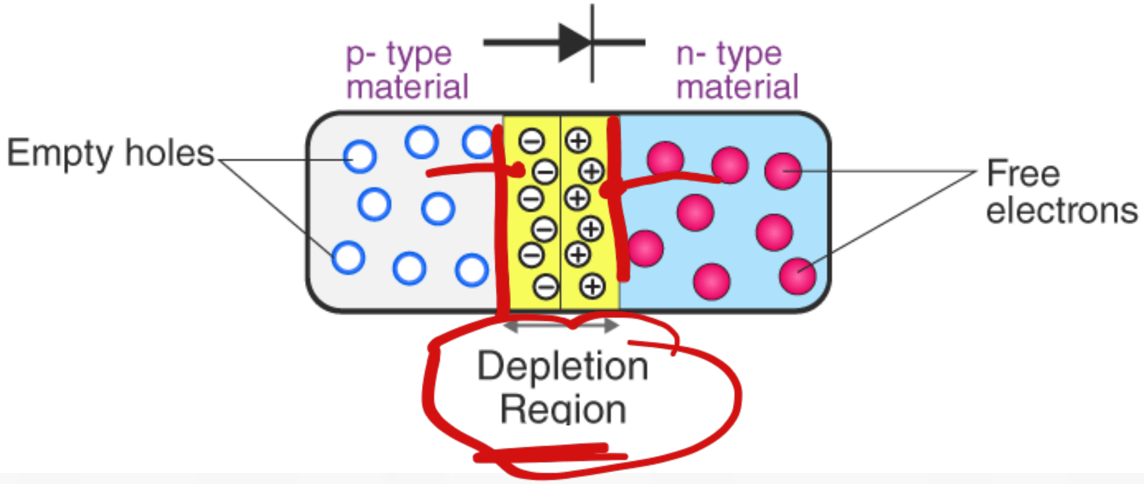




(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.



(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows between the positive and negative charges in the depletion region represent the electric field.

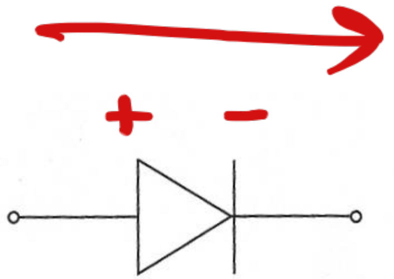


Before the *pn* junction is formed, recall that there are as many electrons as protons in the *n*-type material, making the material neutral in terms of net charge. The same is true for the *p*-type material.

When the *pn* junction is formed, the *n* region loses free electrons as they diffuse across the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the *p* region loses holes as the electrons and holes combine. This creates a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the **depletion region**, as shown in Figure 1–18(b). The term *depletion* refers to the fact that the region near the *pn* junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. Keep in mind that the depletion region is formed very quickly and is very thin compared to the *n* region and *p* region.

Diodes

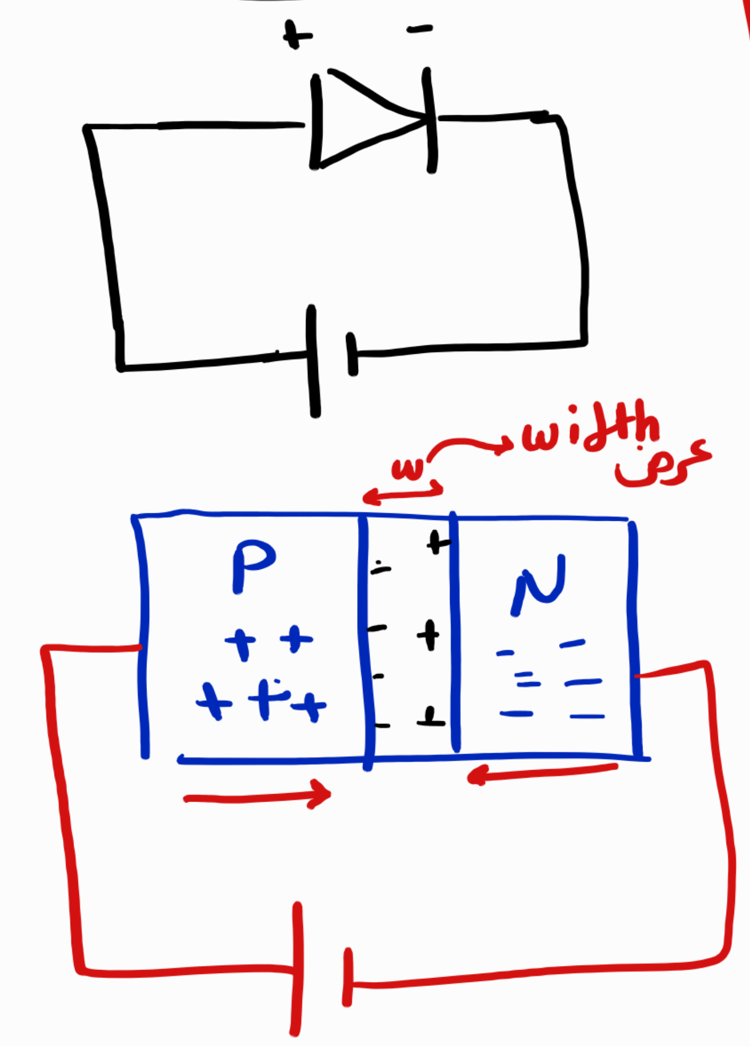
It is represented by the following symbol, where the arrow indicates the direction of positive current flow.



The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium

Forward & Reverse Diode

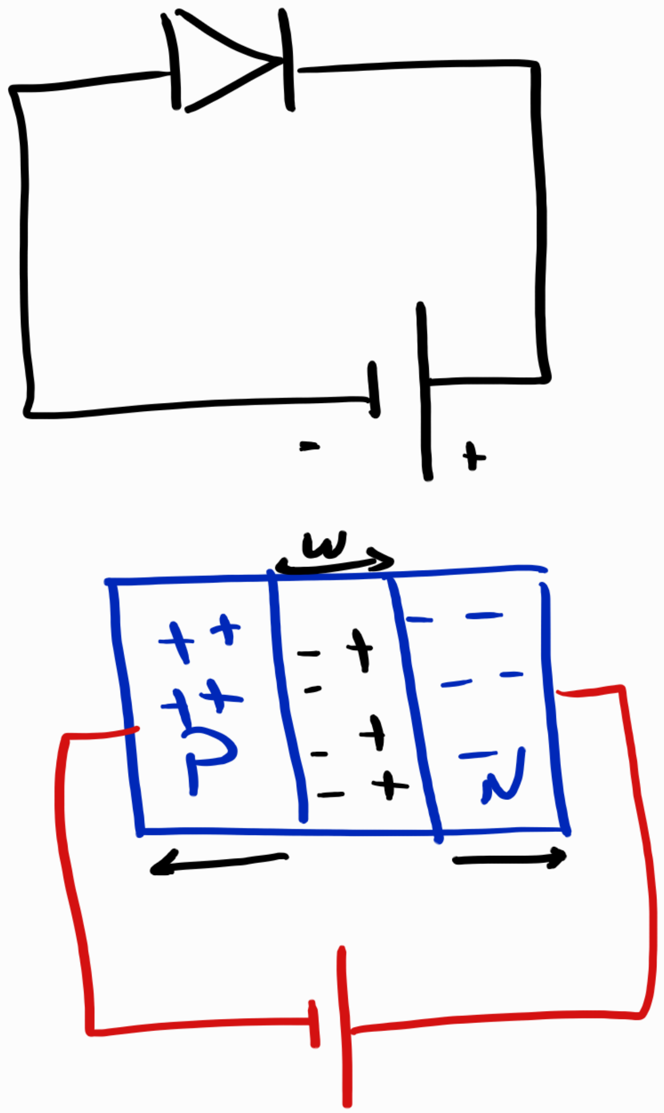
Forward



widt ↓

I ↑

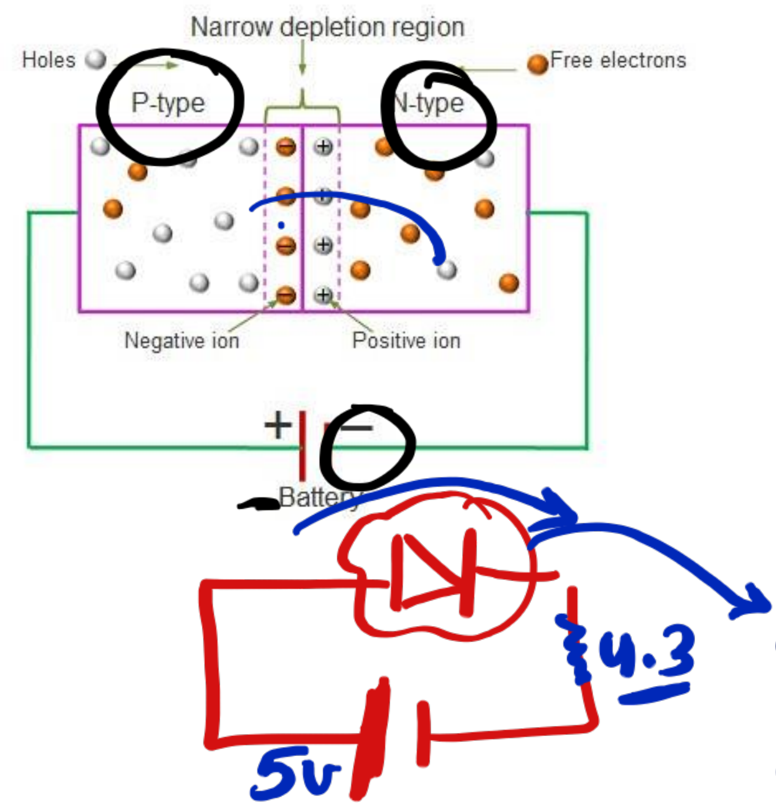
Reverse



w ↑

$I \simeq 0$

PN Junction Diode in forward Bias



When a PN-junction diode is connected in a forward bias by giving a positive voltage to the P-type material and a negative voltage to the N-type terminal. If the external voltage becomes more than the value of the potential barrier (estimate 0.7 V for Si and 0.3V for Ge), the opposition of the potential barriers will be overcome, and the flow of current will start. Because the negative voltage repels electrons near to the junction by giving them the energy to combine and cross over with the holes being pushed in the opposite direction to the junction by the positive voltage.

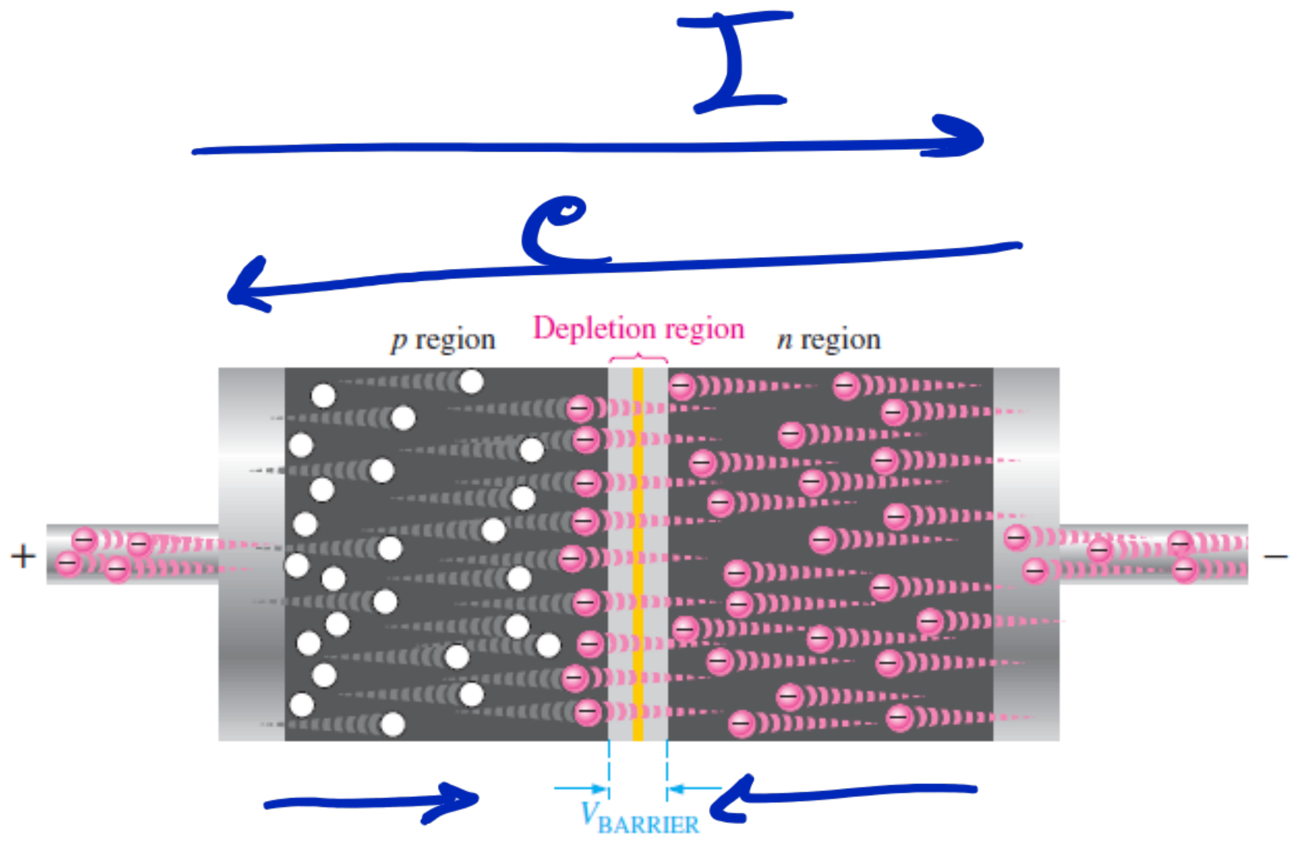
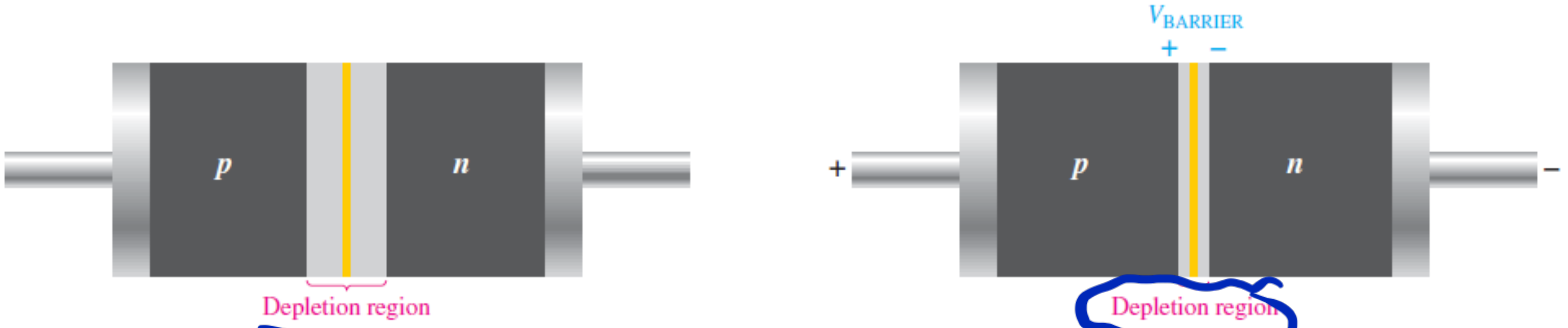


FIGURE 2–4

A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

The Effect of Forward Bias on the Depletion Region As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on the other side of the *pn* junction, the number of negative ions is reduced. This reduction in positive and negative ions during forward bias causes the depletion region to narrow, as indicated in Figure 2–5.

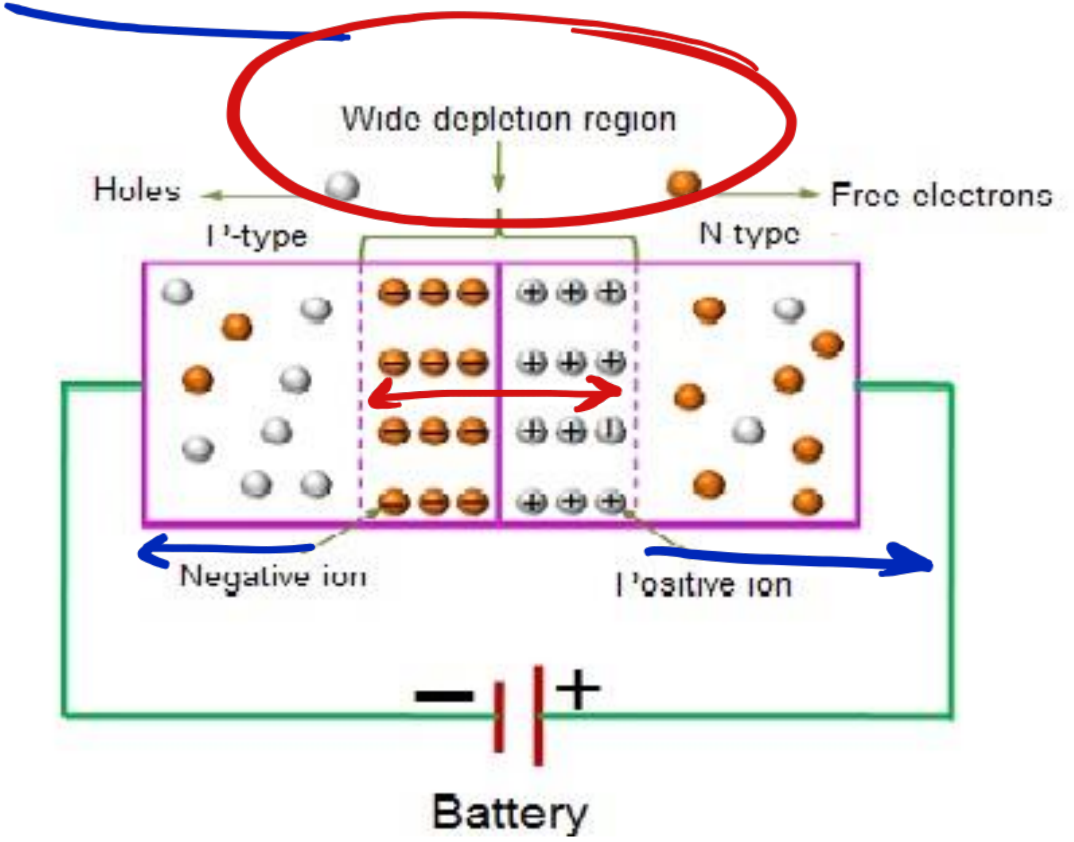


(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

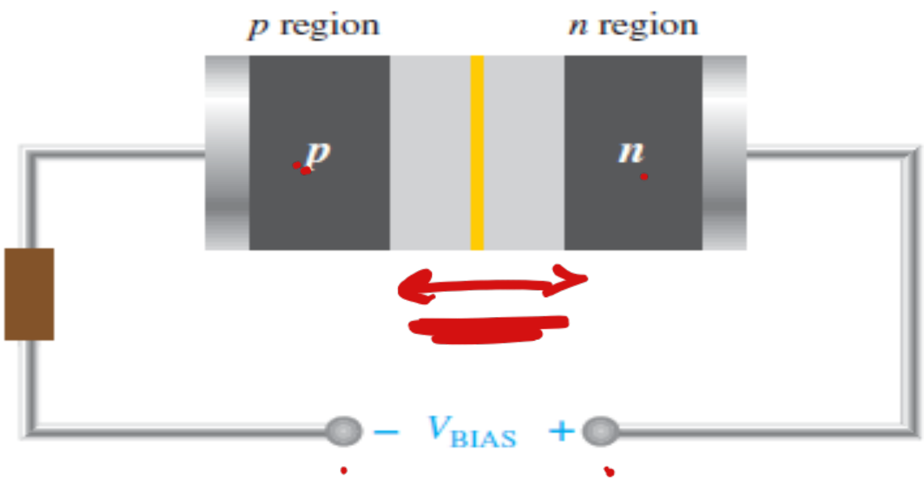
PN Junction Diode in Reverse Bias

- When the +Ve voltage is applied to the N-type material, then it attracts the electrons near the positive electrode and goes away from the junction, whereas the holes in the P-type end are also attracted away from the junction near the negative electrode.



Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 2–6 shows a dc voltage source connected across a diode in the direction to produce reverse bias. This external bias voltage is designated as V_{BIAS} just as it was for forward bias. Notice that the positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region. Also note that the depletion region is shown much wider than in forward bias or equilibrium.



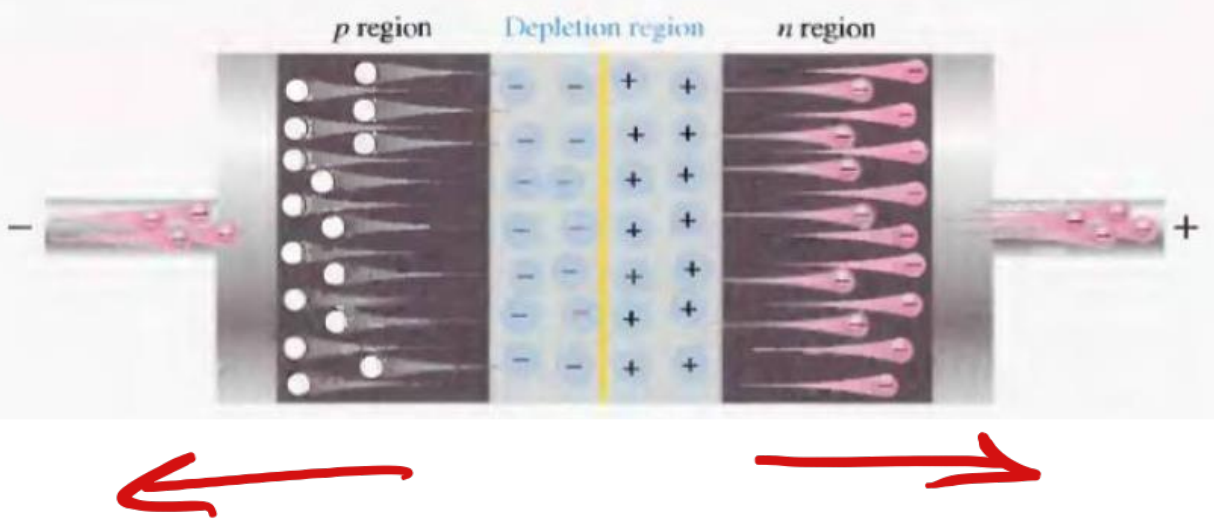


FIGURE 1–24

The diode during the short transition time immediately after reverse-bias voltage is applied.

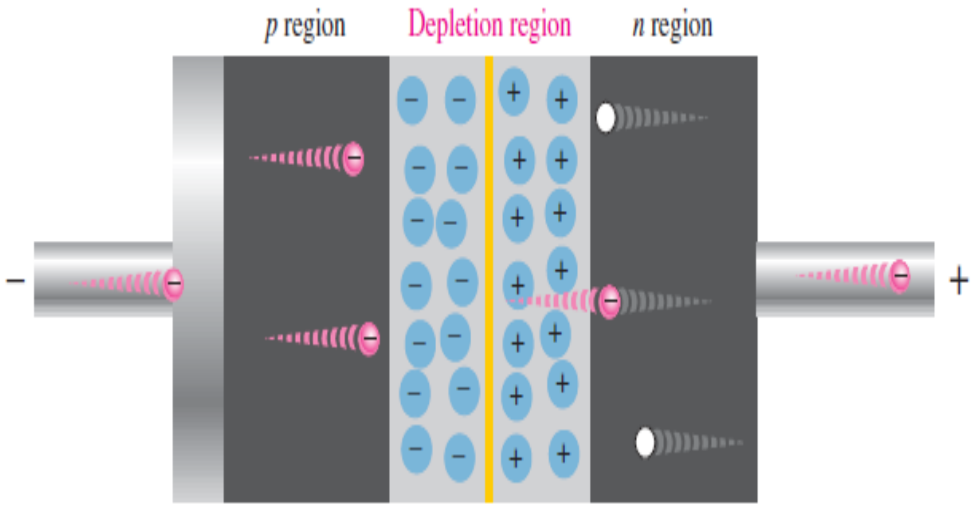
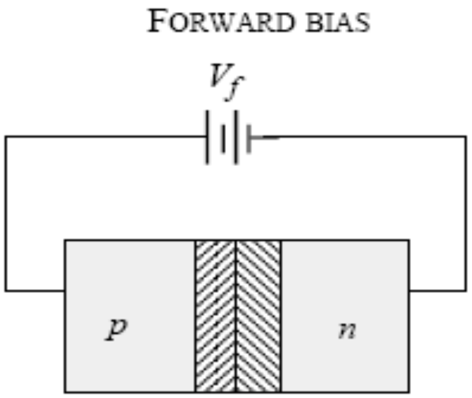


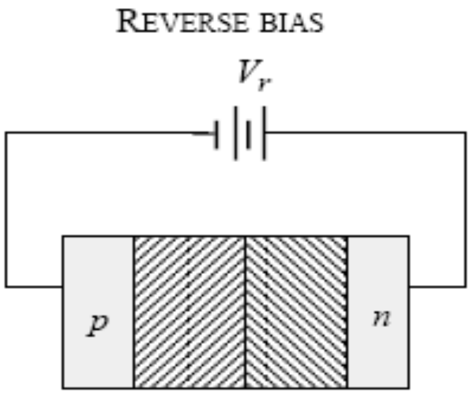
FIGURE 2–8

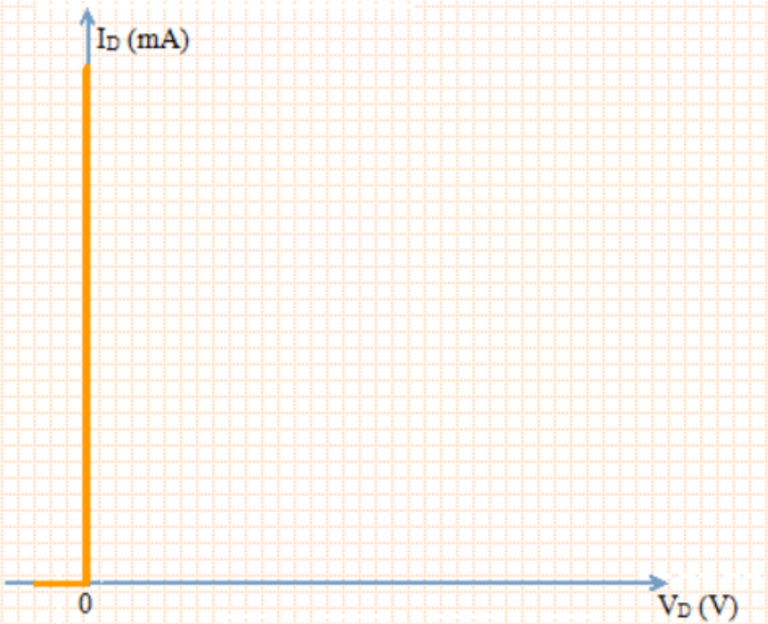
The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.

Forward Bias and Reverse Bias

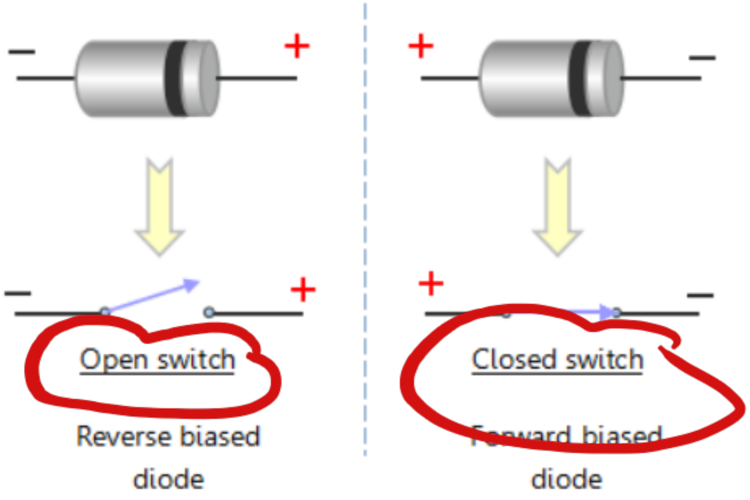
- Forward Bias : Connect p region of the Diode to positive of supply…n region of Diode to negative of supply
- Reverse Bias: Connect p region of the Diode to negative of supply…n region of diode to positive of supply.







Ideal characteristics

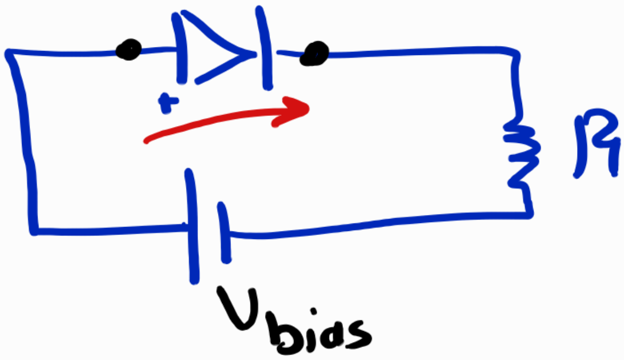


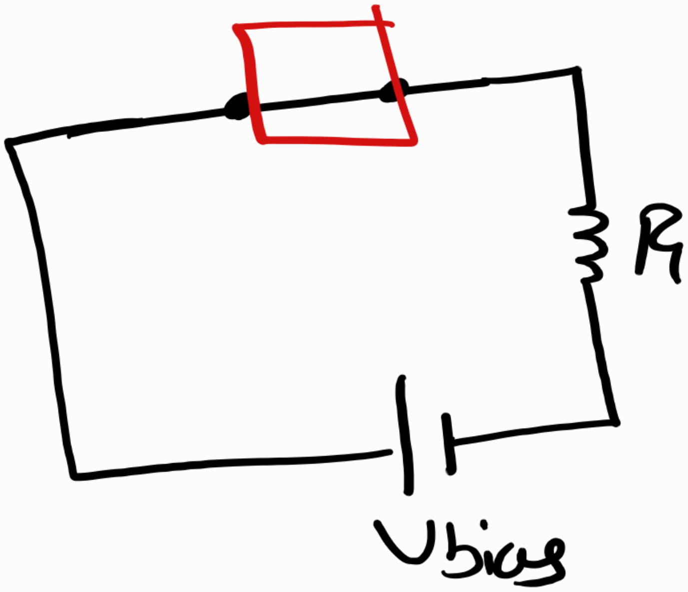
Ideal diode models

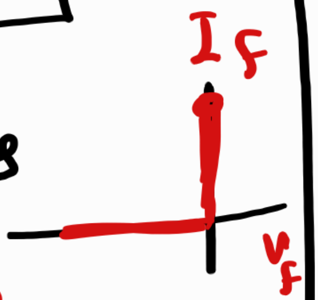
Ohm law ⇒ $V = IR$

① Ideal

Forward



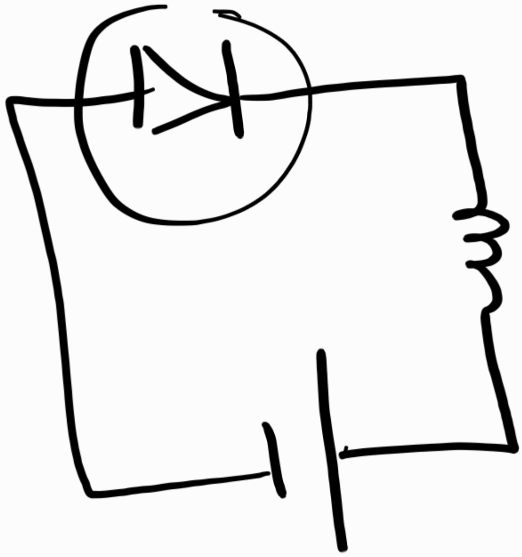


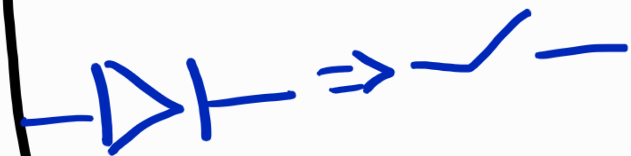


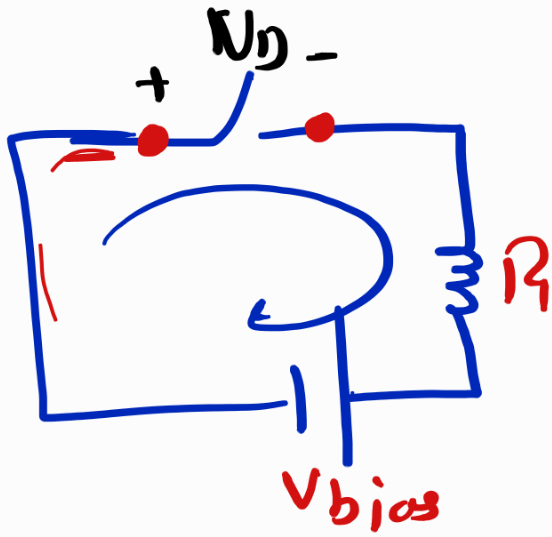
$V_D = \text{Zero}$

$$I_D = \frac{V_{bias}}{R}$$

Reverse



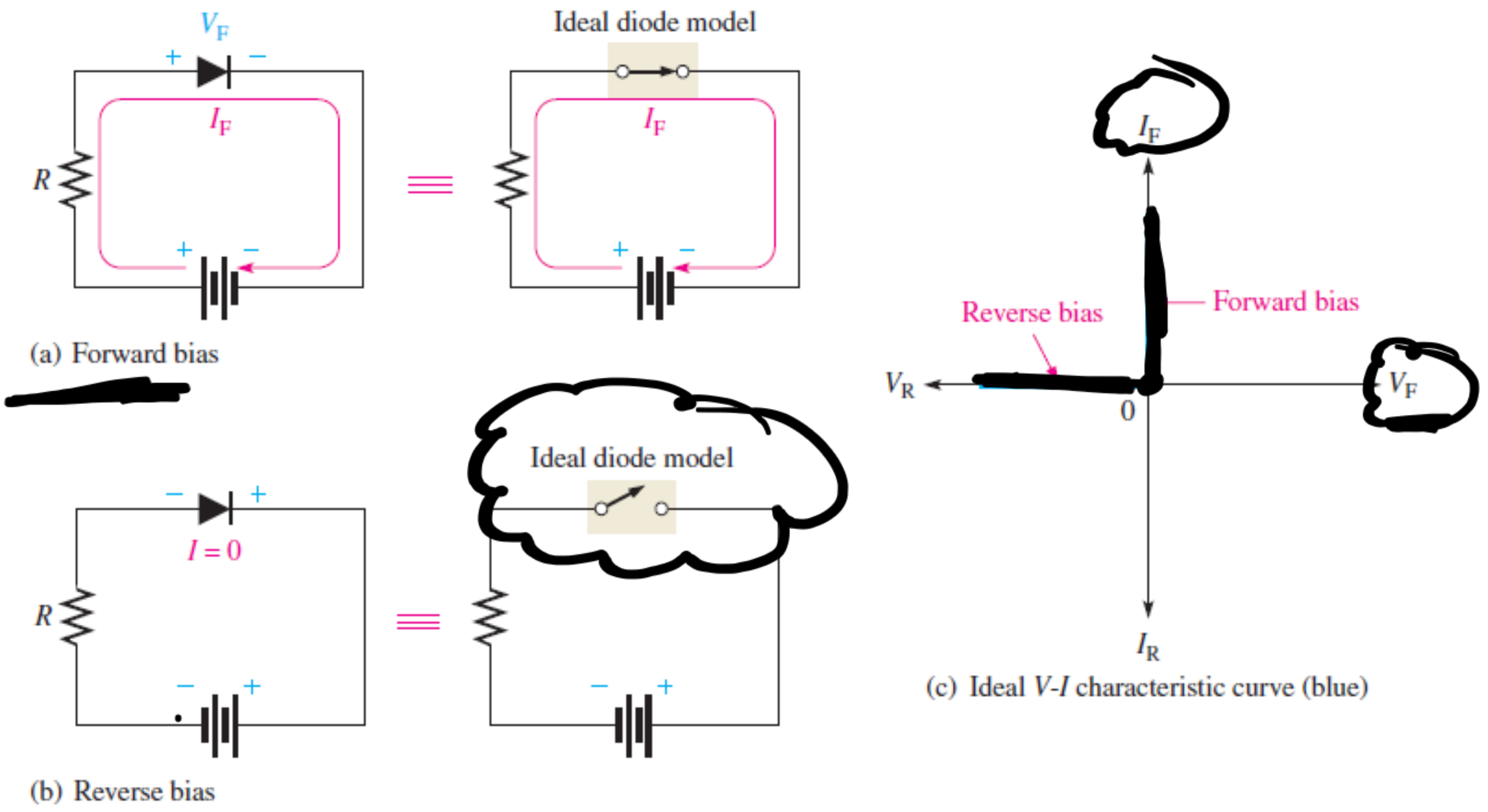




$I = \text{Zero}$

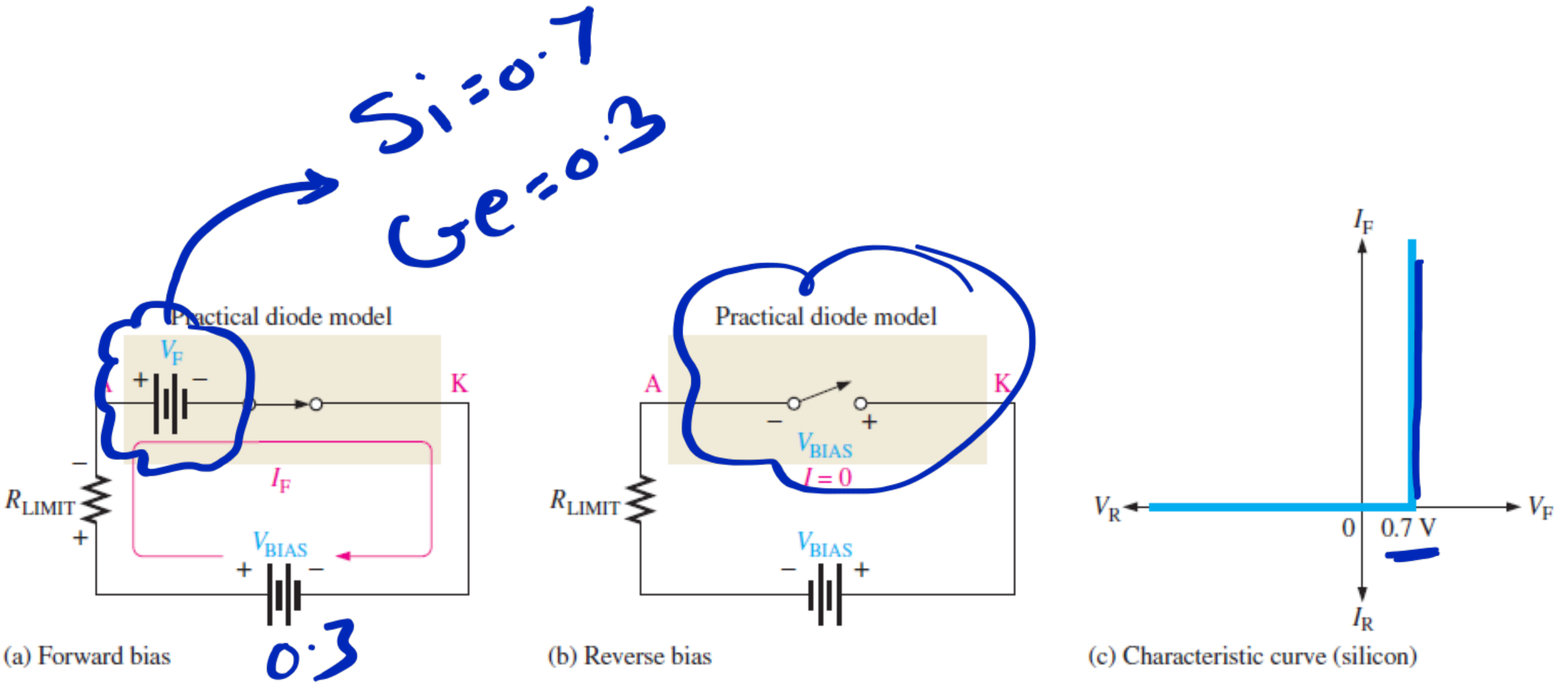
$$V_{bias} + V_D + IR = 0$$

$$V_D = -V_{bias}$$



▲ FIGURE 2–15

The ideal model of a diode.

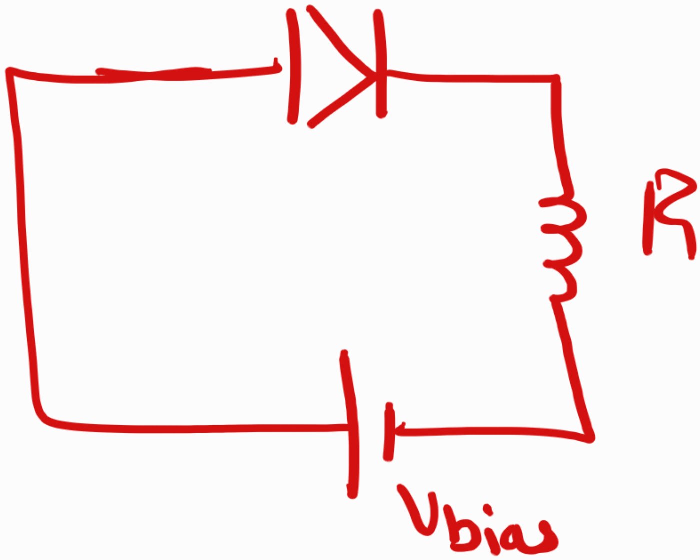


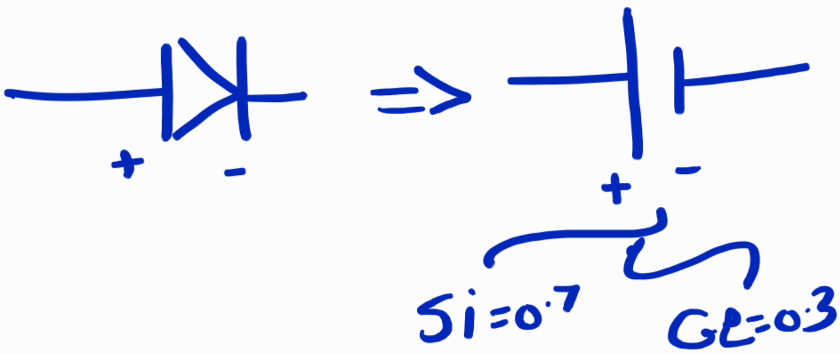
▲ FIGURE 2–16

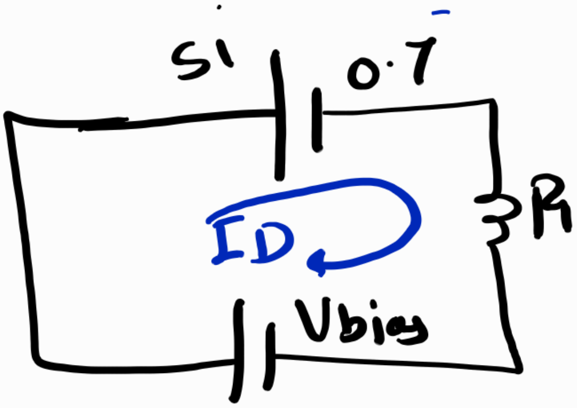
The practical model of a diode.

Practical

Forward







$V_D = 0.7$

$-V_{bias} + 0.7 + I_D R = 0$

$$I_D = \frac{V_{bias} - 0.7}{R}$$

Reverse

نفس Ideal

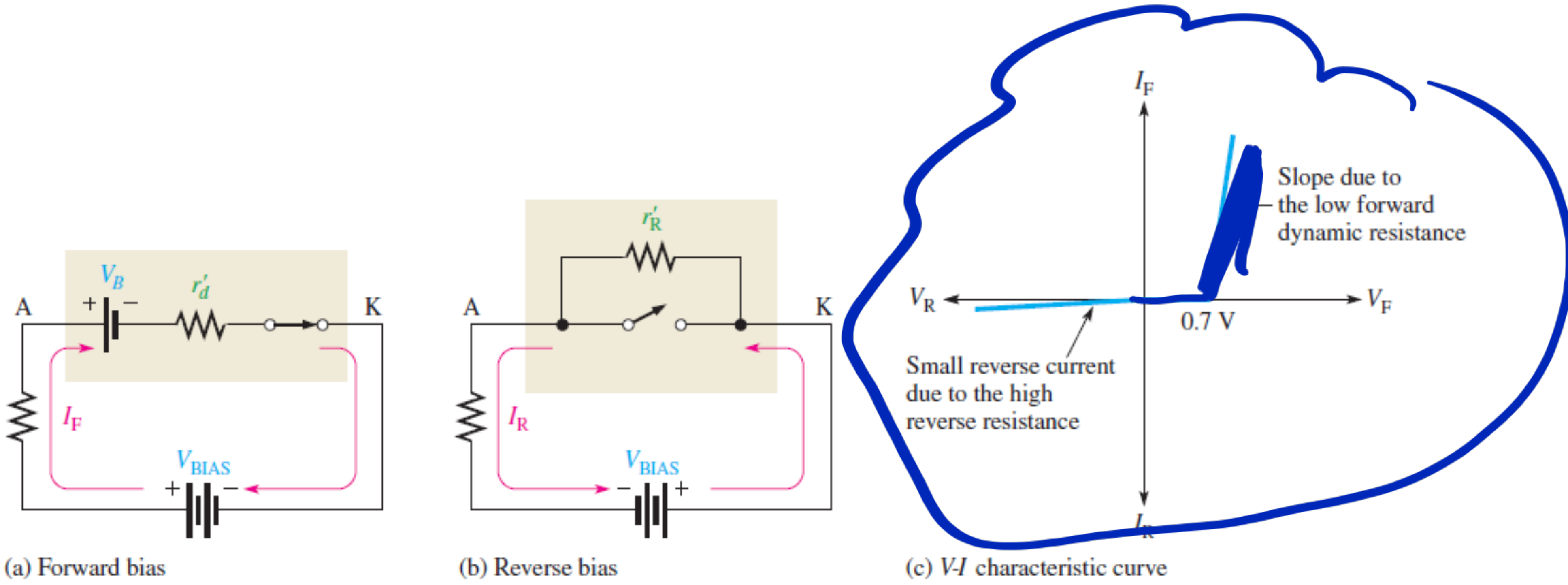
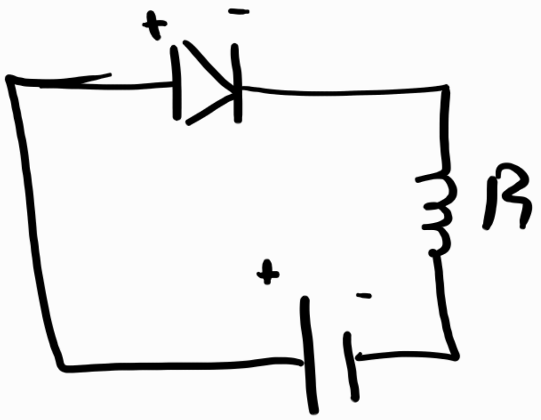


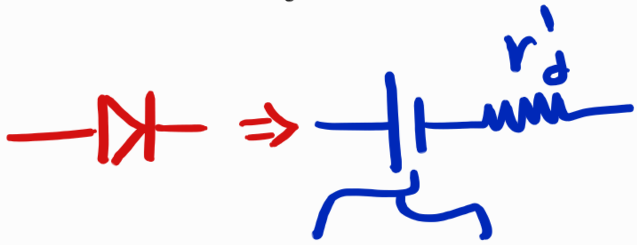
FIGURE 2–17

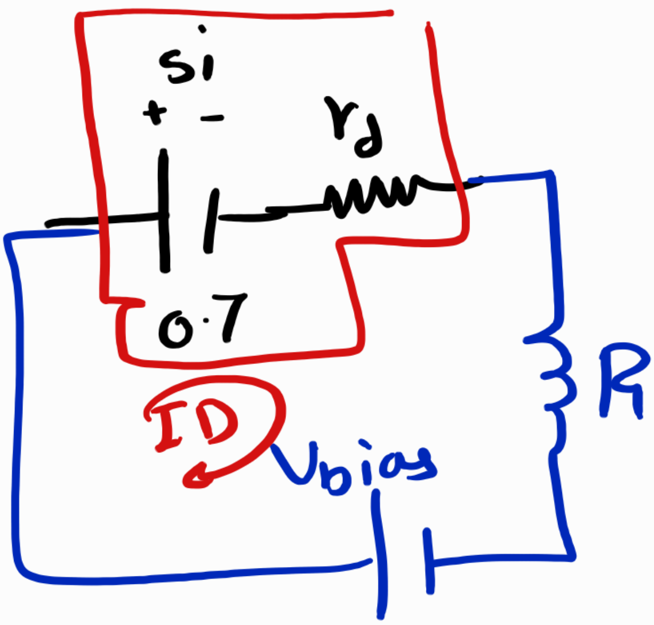
The complete model of a diode.

Complete Model

Forward $r'_d <<$





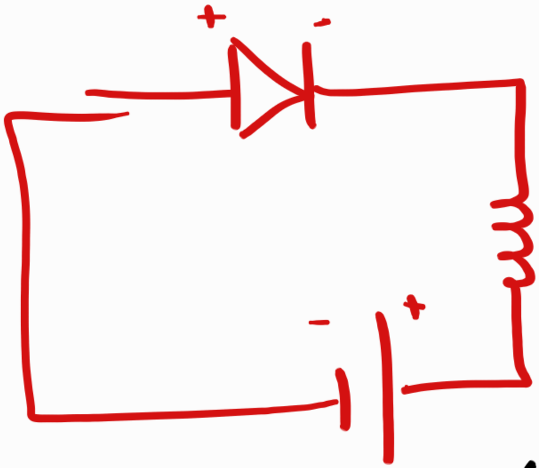


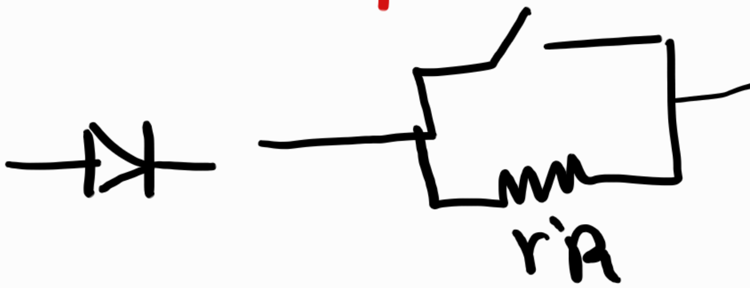
$$-V_{bias}+0.7+I_D r_d+I_D R=0$$

$$I_D(r_d+R)=V_{bias}-0.7$$

$$I_D=\frac{V_{bias}-0.7}{I_D}$$

$r'_R >>$ Reverse



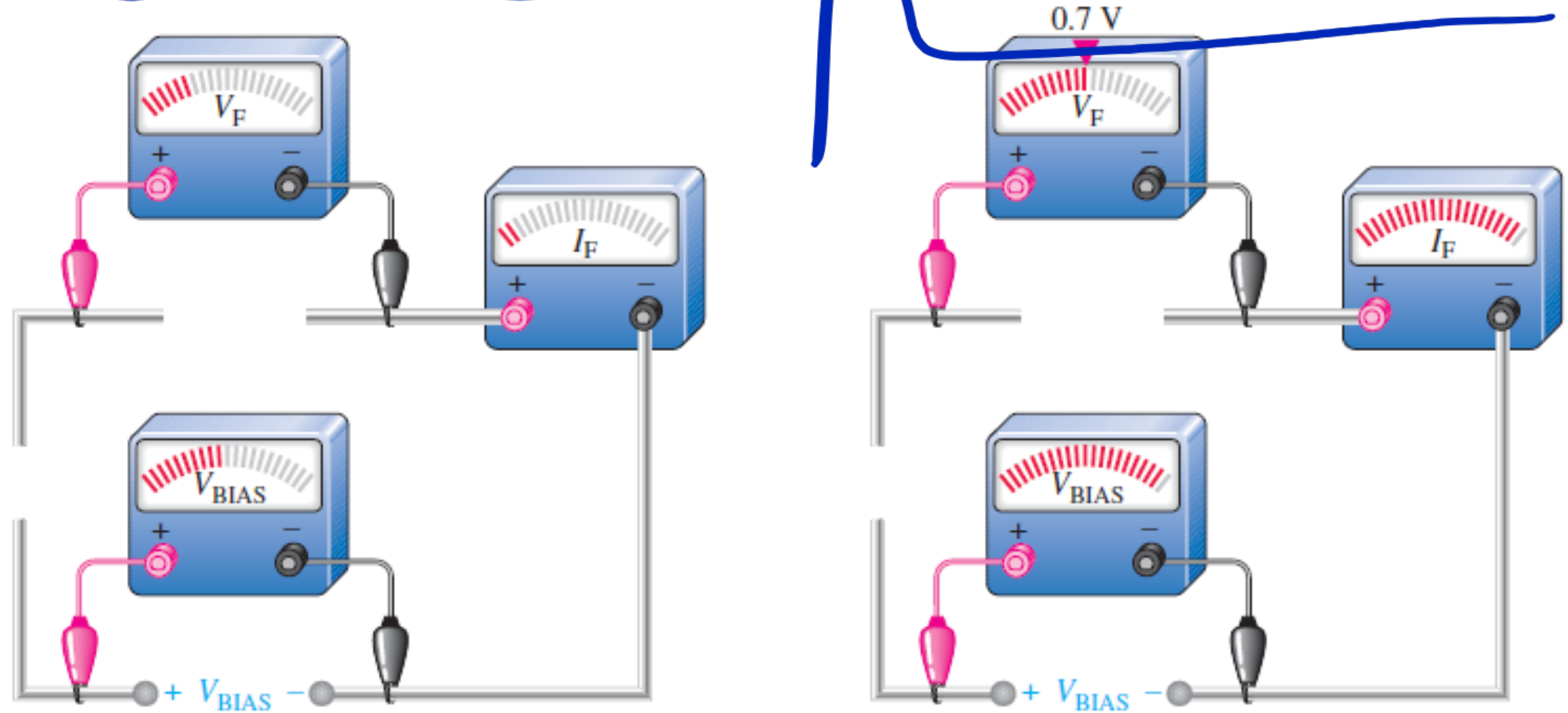


$$V_{bias}+I_D r'_R+I_D R=0$$

$$I_D=\frac{-V_{bias}}{r'_R+R}$$

$V_D = 0.7 + I_D r_d$

$V_D = I_D * r'_d$



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

I-V Characteristics of Practical Diode

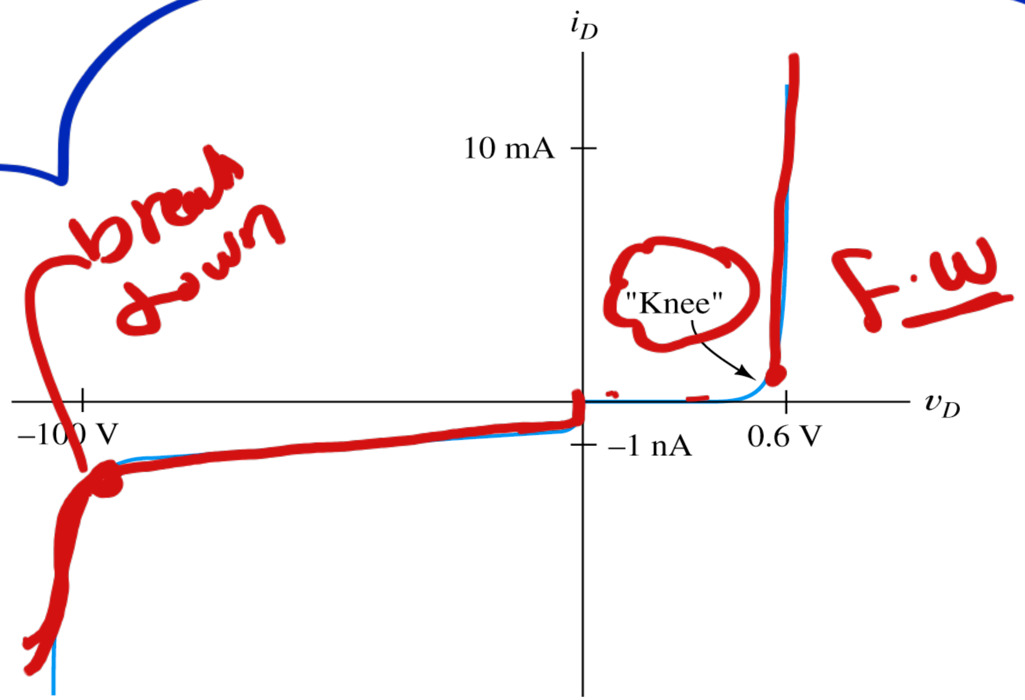
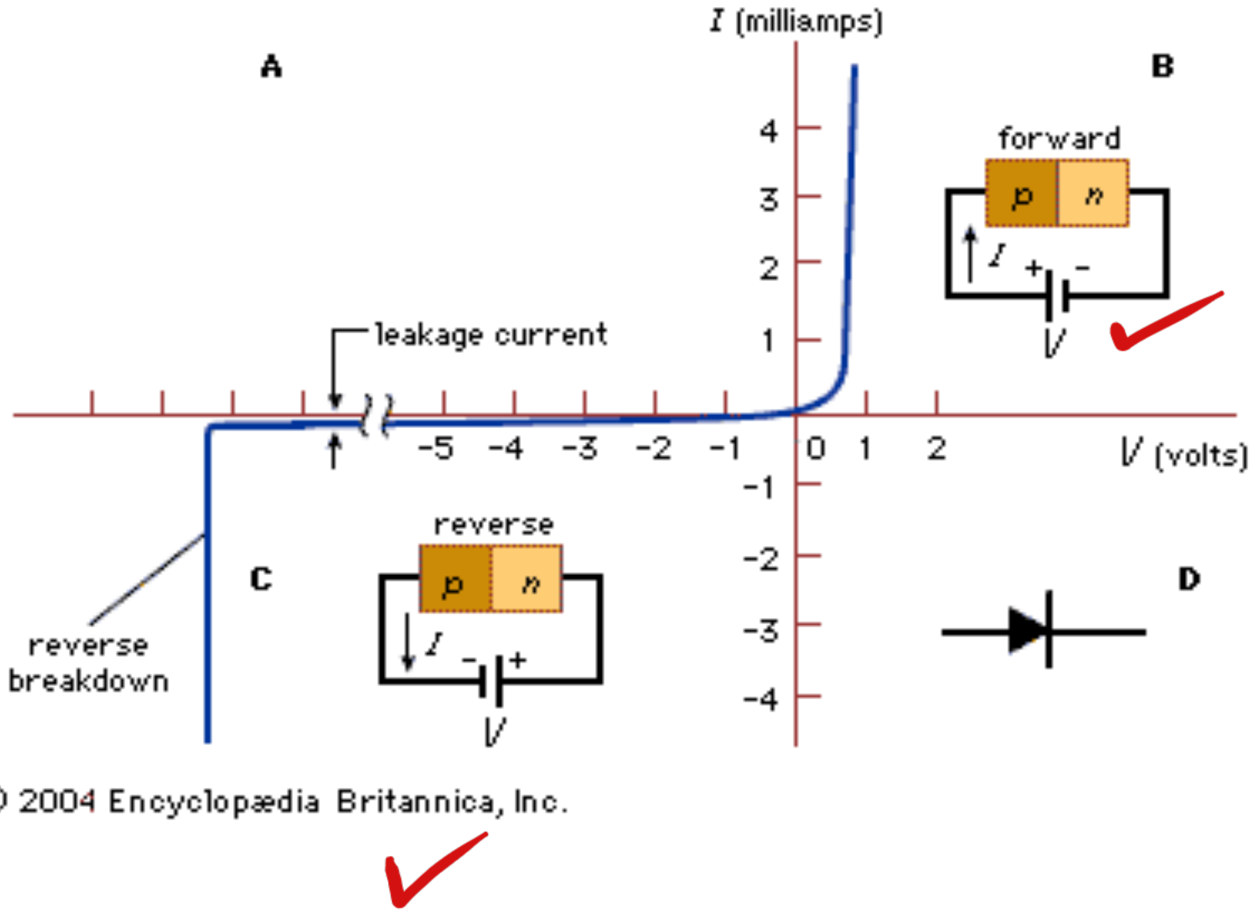


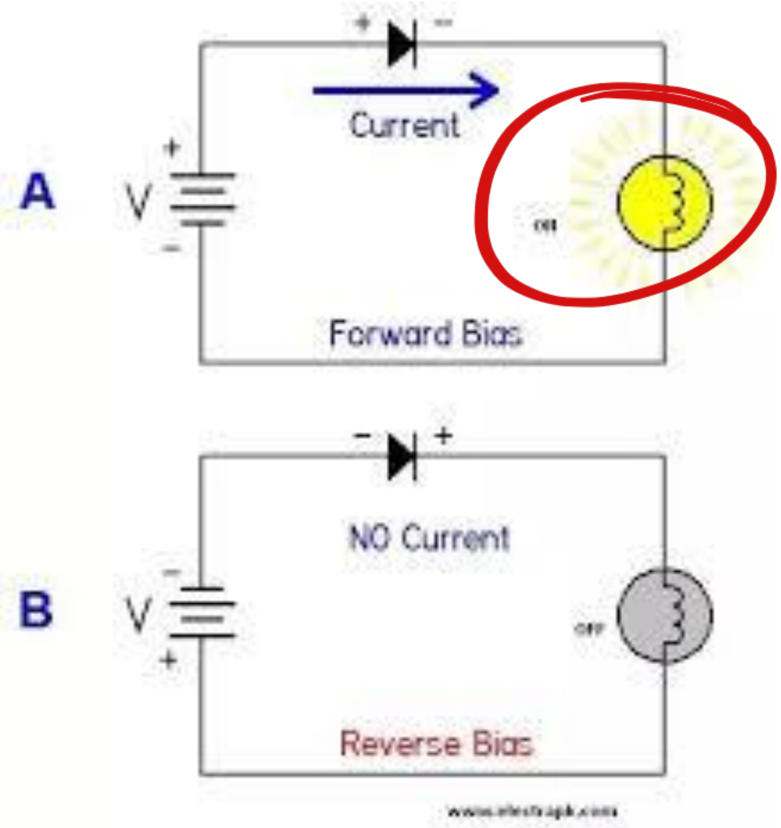
Figure 10.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.


I (milliamps)
A
B
forward
p
n
I
+
-
V
4
3
2
1
leakage current
-5
-4
-3
-2
-1
0
1
2
V (volts)
-1
-2
-3
-4
reverse
p
n
I
-
+
V
C
D
reverse
breakdown

Characteristics of Diode

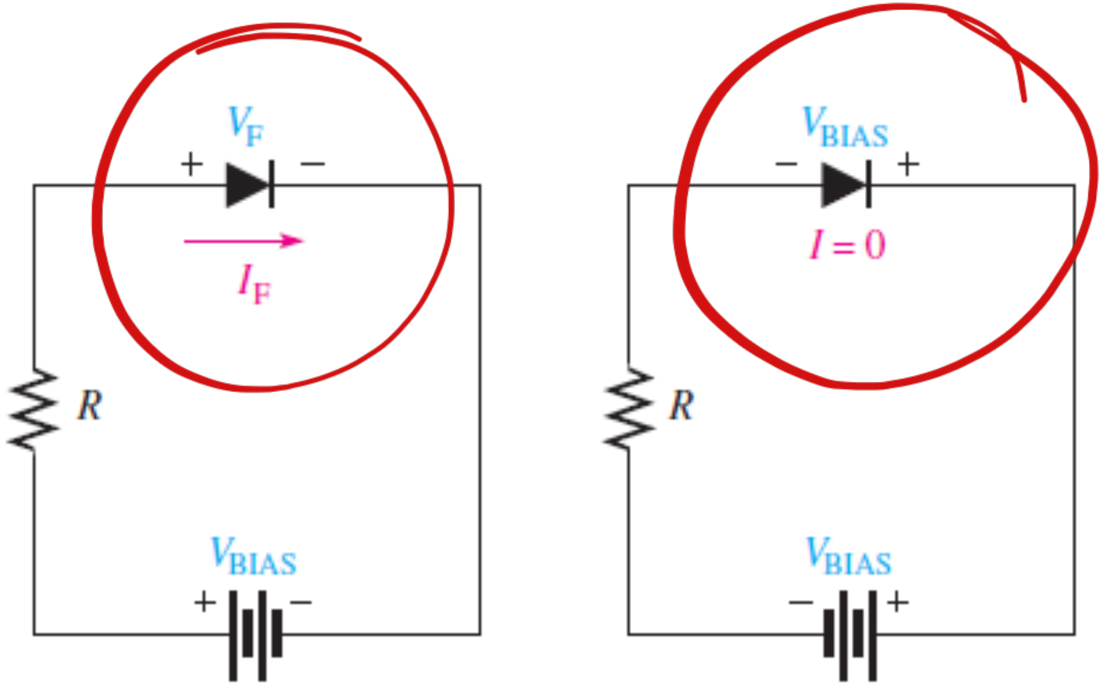
- Diode always conducts in one direction.
- Diodes always conduct current when "Forward Biased" (Zero resistance)
- Diodes do not conduct when Reverse Biased

  (Infinite resistance)



▶ FIGURE 2–14

Forward-bias and reverse-bias connections showing the diode symbol.



(a) Forward bias

(b) Reverse bias

Review Questions

1. Valence electrons are

(a) in the closest orbit to the nucleus
(b) in the most distant orbit from the nucleus
(c) in various orbits around the nucleus
(d) not associated with a particular atom

2. A positive ion is formed when

(a) a valence electron breaks away from the atom
(b) there are more holes than electrons in the outer orbit
(c) two atoms bond together
(d) an atom gains an extra valence electron

3. The energy band in which free electrons exist is the

(a) first band
(b) second band
(c) conduction band
(d) valence band

4. Electron-hole pairs are produced by

(a) recombination
(b) thermal energy
(c) ionization
(d) doping

5. Recombination is when

(a) an electron falls into a hole
(b) a positive and a negative ion bond together
(c) a valence electron becomes a conduction electron
(d) a crystal is formed

6. The current in a semiconductor is produced by

(a) electrons only **(b)** holes only **(c)** negative ions **(d)** both electrons and holes

7. In an intrinsic semiconductor,

(a) there are no free electrons

(b) the free electrons are thermally produced

(c) there are only holes

(d) there are as many electrons as there are holes

(e) answers (b) and (d)

8. The process of adding an impurity to an intrinsic semiconductor is called

(a) doping **(b)** recombination **(c)** atomic modification **(d)** ionization

9. A trivalent impurity is added to silicon to create

(a) germanium **(b)** a *p*-type semiconductor

(c) an *n*-type semiconductor **(d)** a depletion region

10. The purpose of a pentavalent impurity is to

(a) reduce the conductivity of silicon **(b)** increase the number of holes

(c) increase the number of free electrons **(d)** create minority carriers

11. The majority carriers in an *n*-type semiconductor are

(a) holes **(b)** valence electrons **(c)** conduction electrons **(d)** protons

12. Holes in an *n*-type semiconductor are

(a) minority carriers that are thermally produced

(b) minority carriers that are produced by doping

(c) majority carriers that are thermally produced

(d) majority carriers that are produced by doping

13. What are the pentavalent impurities? NTypeN

14. What are the trivalent impurities? P Typ

1. The term *bias* means

(a) the ratio of majority carriers to minority carriers

(b) the amount of current across a diode

(c) a dc voltage is applied to control the operation of a device

(d) neither (a), (b), nor (c)

2. To forward-bias a diode,

(a) an external voltage is applied that is positive at the anode and negative at the cathode

(b) an external voltage is applied that is negative at the anode and positive at the cathode

(c) an external voltage is applied that is positive at the *p* region and negative at the *n* region

(d) answers (a) and (c)

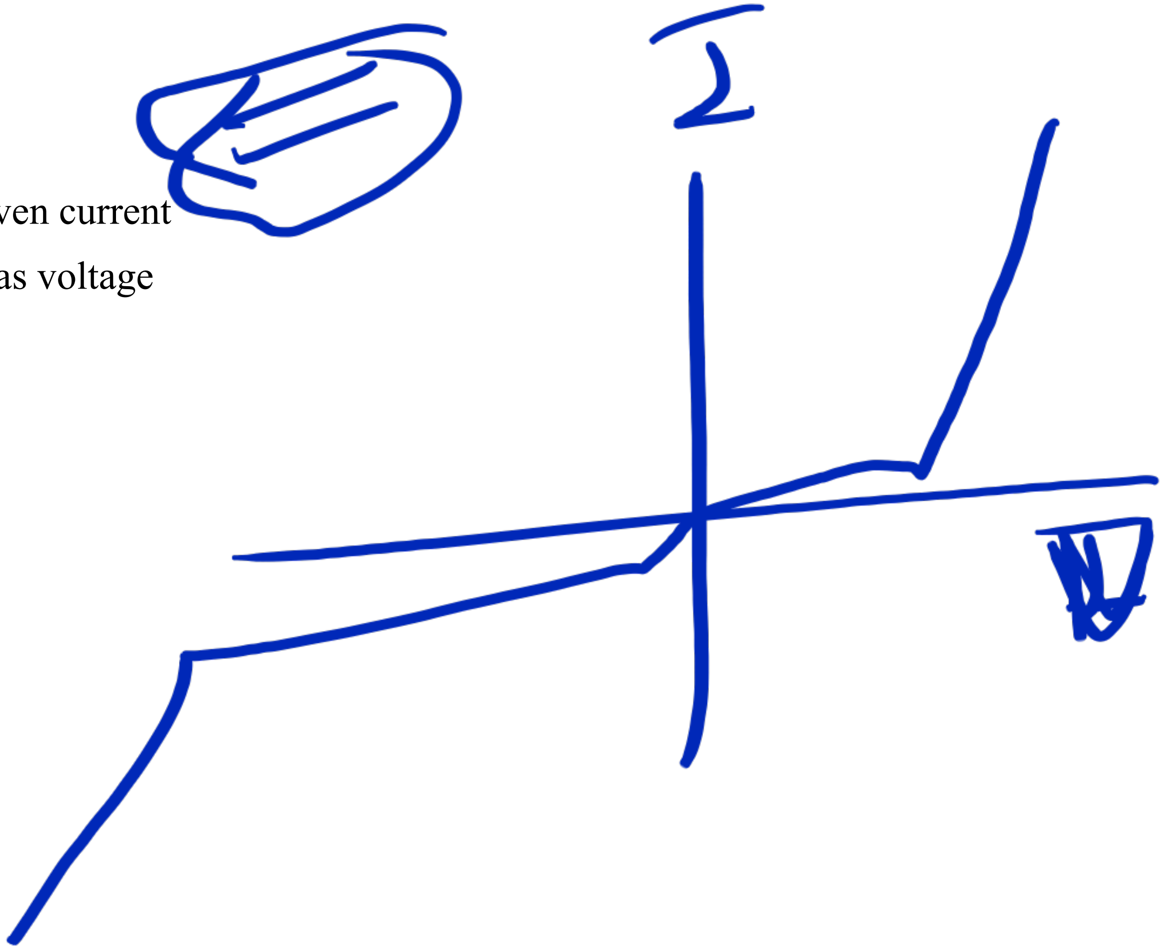
1. The *V*-*I* curve for a diode shows

(a) the voltage across the diode for a given current

(b) the amount of current for a given bias voltage

(c) the power dissipation

(d) none of these



1. For each of the energy diagrams in Figure 1–21, determine the class of material based on relative comparisons.

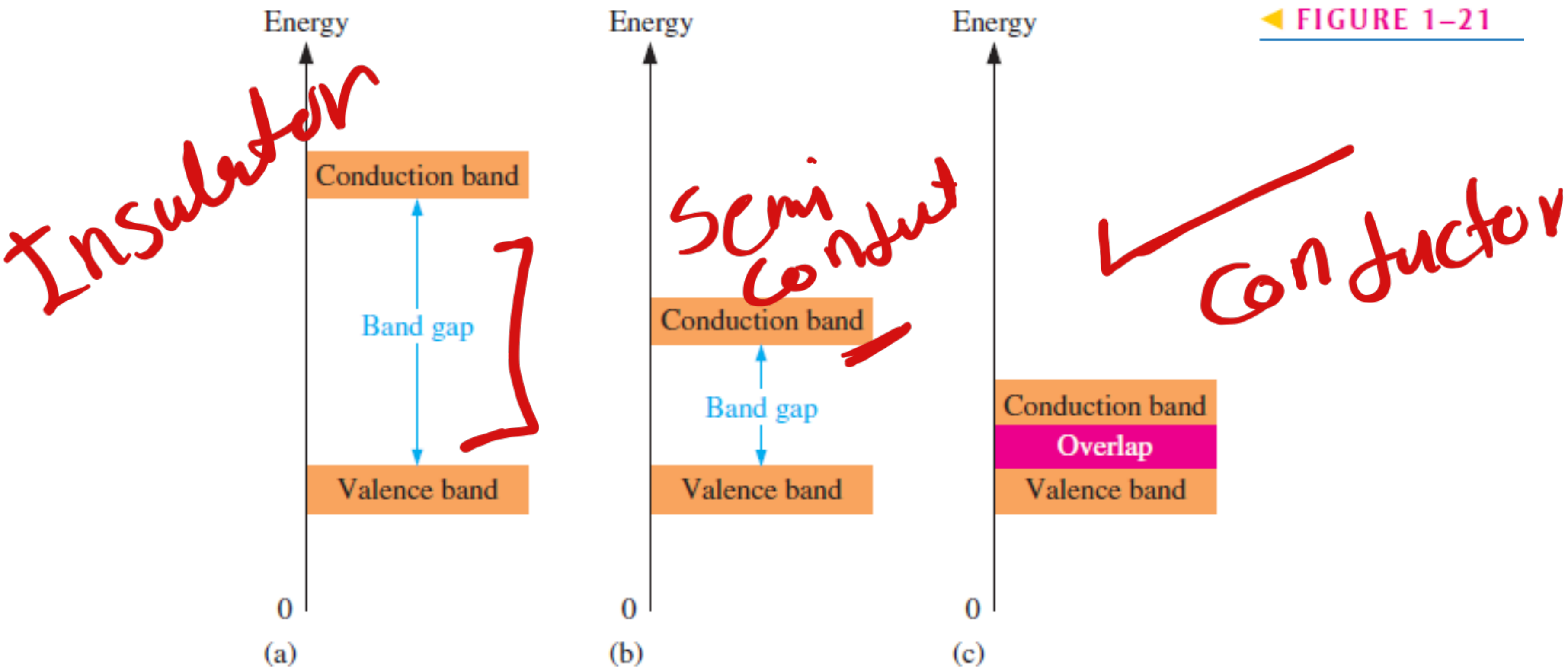


FIGURE 1–21