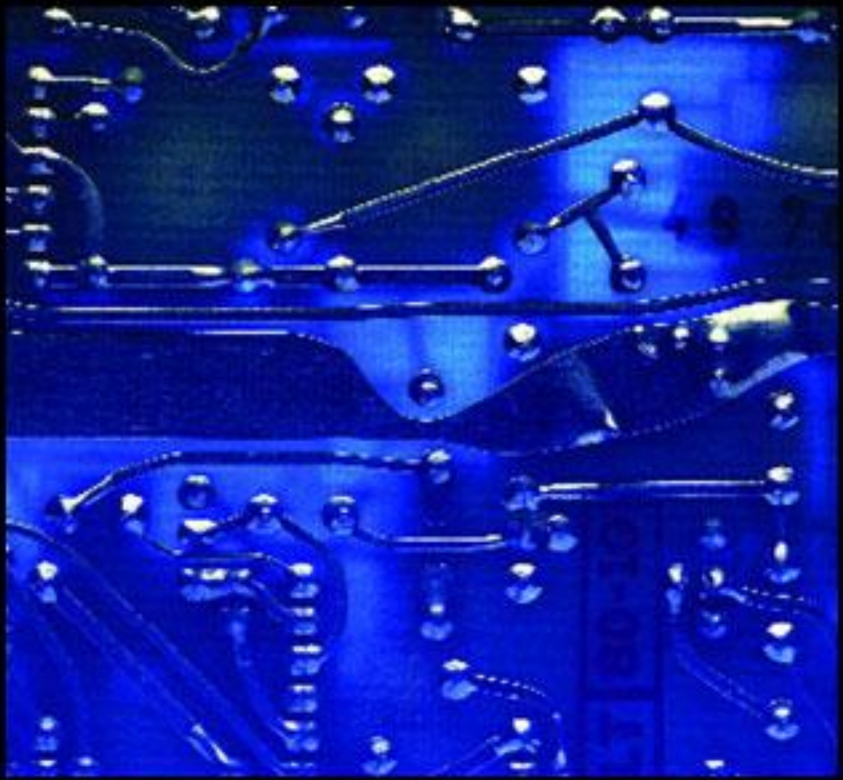
ELECTRONIC DEVICES AND CIRCUIT THEORY

TENTH EDITION



BOYLESTAD

PEARSON

Chapter 1:
Semiconductor Diodes

Semiconductor Materials: Ge, Si, and GaAs

Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.

- They fall into two classes : single crystal and compound
- Single crystal : Germanium (Ge) and silicon (Si).
- Compound : gallium arsenide (GaAs),
  cadmium sulfide (CdS),
  gallium nitride (GaN),
  gallium arsenide phosphide (GaAsP)

The three semiconductors used most frequently in the construction of electronic devices are **Ge**, **Si**, and **GaAs**.

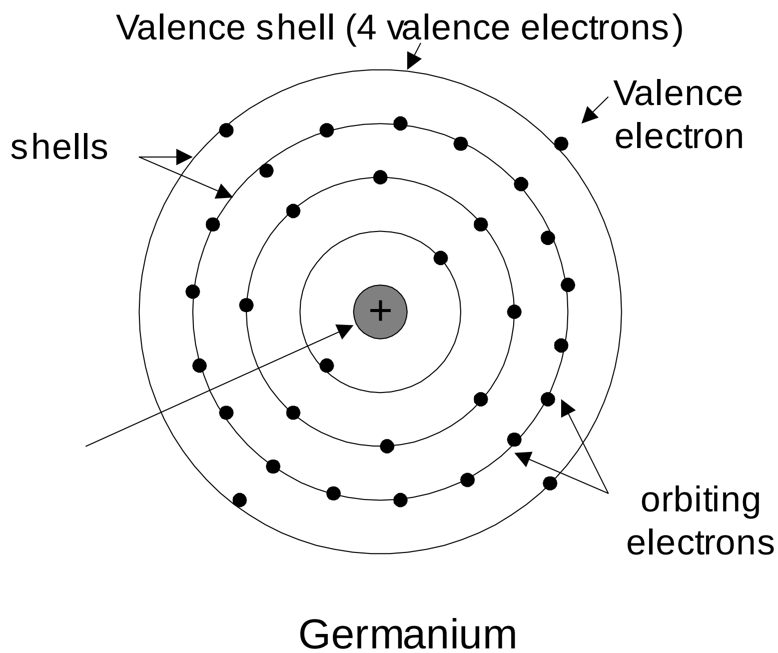
Group → Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

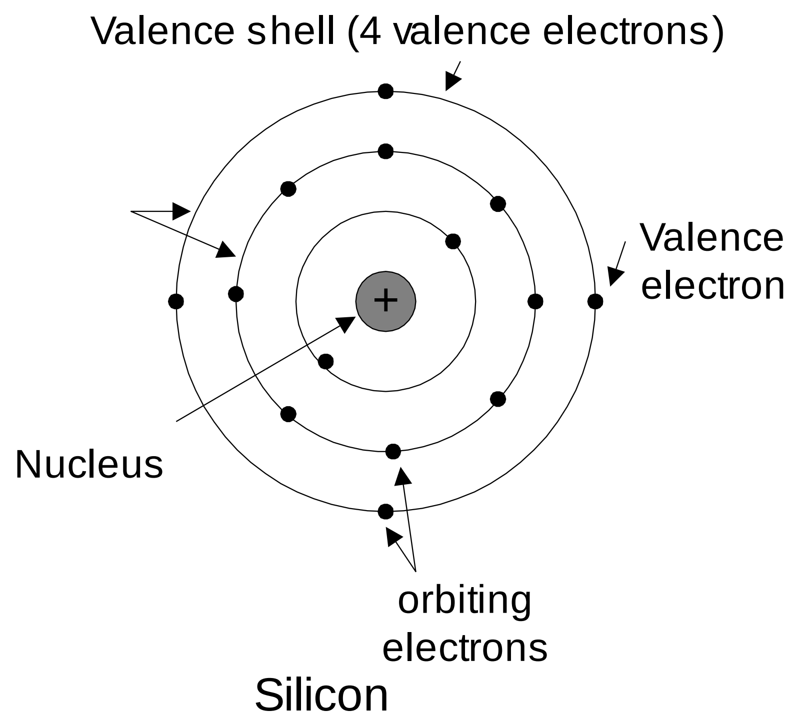
History

- Diode , in 1939 was using Ge
- Transistor, in 1947 was using Ge
- In1954 Si was used in Transistor because Si is less temperature sensitive and abundantly available.
- High speed transistor was using GaAs in 1970 (which is 5 times faster compared to Si)
- Si, Ge and GaAs are the semiconductor of choice

Atomic Structure



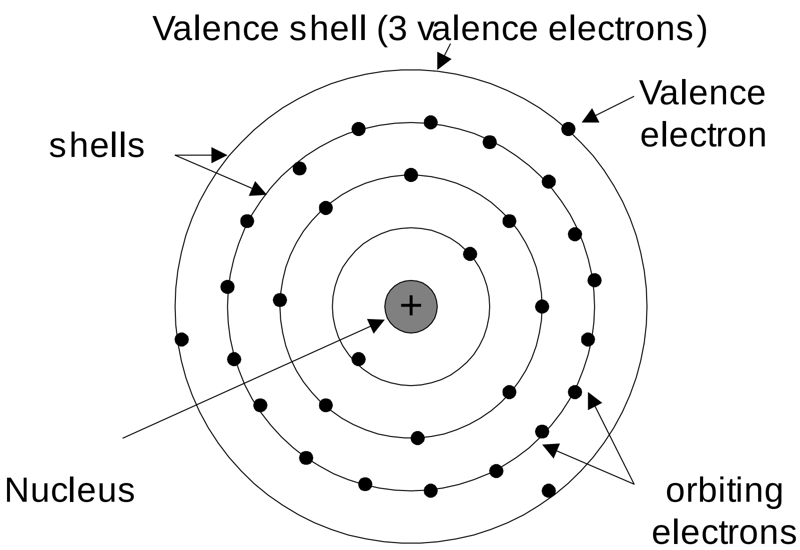
32 orbiting electrons
(tetravalent)



14 orbiting electrons
(Tetravalent)

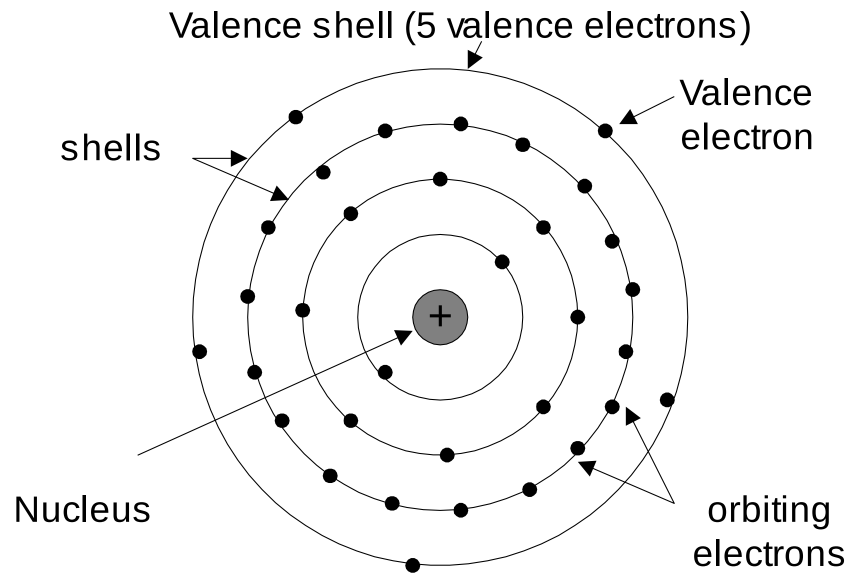
- Valence electrons: electrons in the outermost shell.
- Atoms with four valence electrons are called tetravalent.

Atomic Structure



Gallium

31 orbiting electrons
(trivalent)

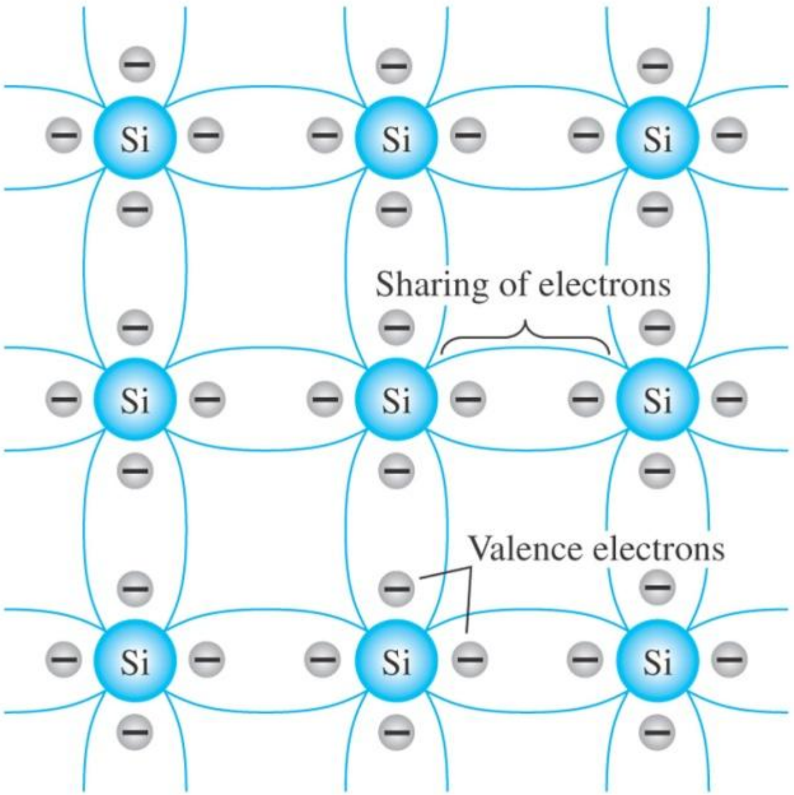


Arsenic

33 orbiting electrons
(pentavalent)

- Atoms with three valence electrons are called trivalent, and those with five are called pentavalent.

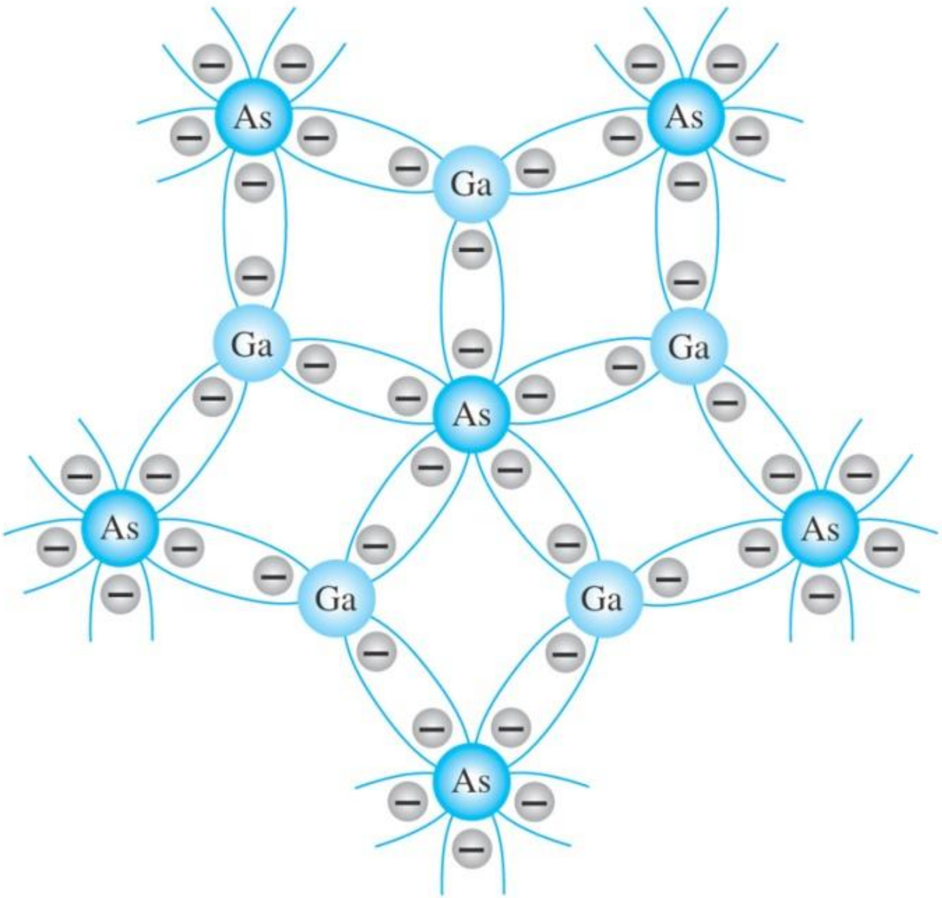
Covalent Bonding



Covalent bonding of Si crystal

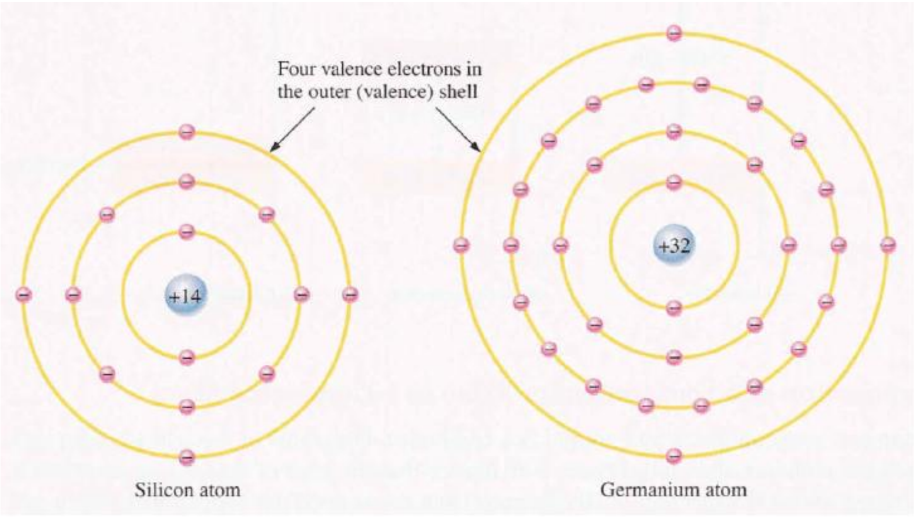
This bonding of atoms, strengthened by the sharing of electrons, is called **covalent bonding**

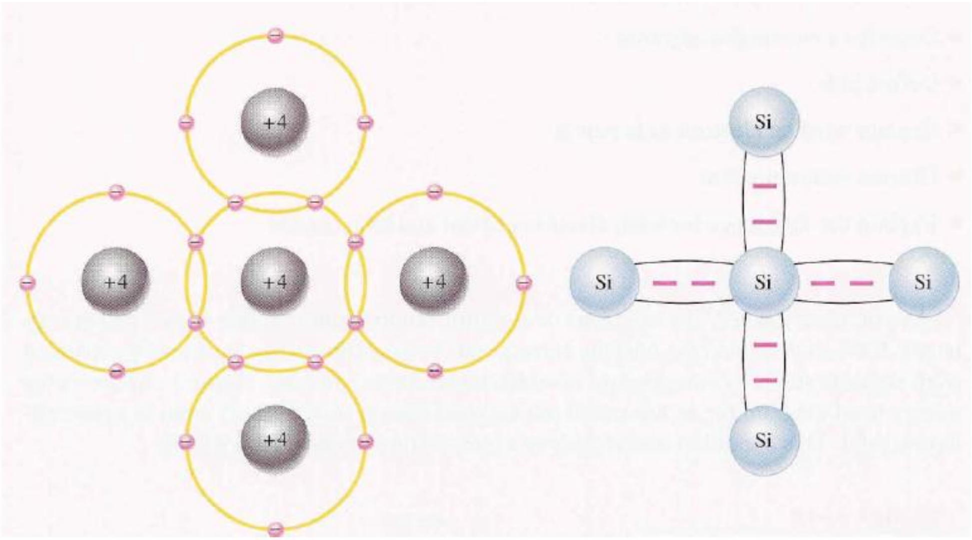
Covalent Bonding



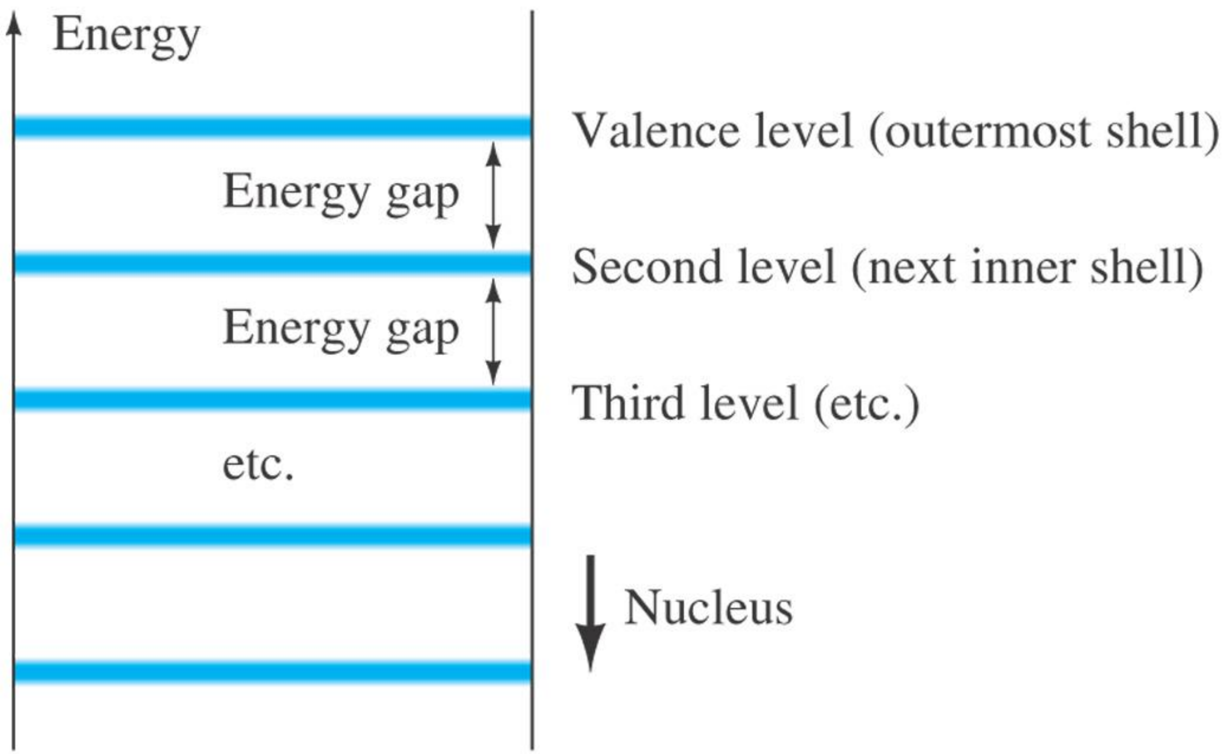
There is sharing of electrons, five electrons provided by As atom and three by the Ga atom.

Covalent bonding of GaAs crystal


Four valence electrons in
the outer (valence) shell
+14
+32
Silicon atom
Germanium atom


+4
+4
+4
+4
+4
Si
Si
Si
Si
Si

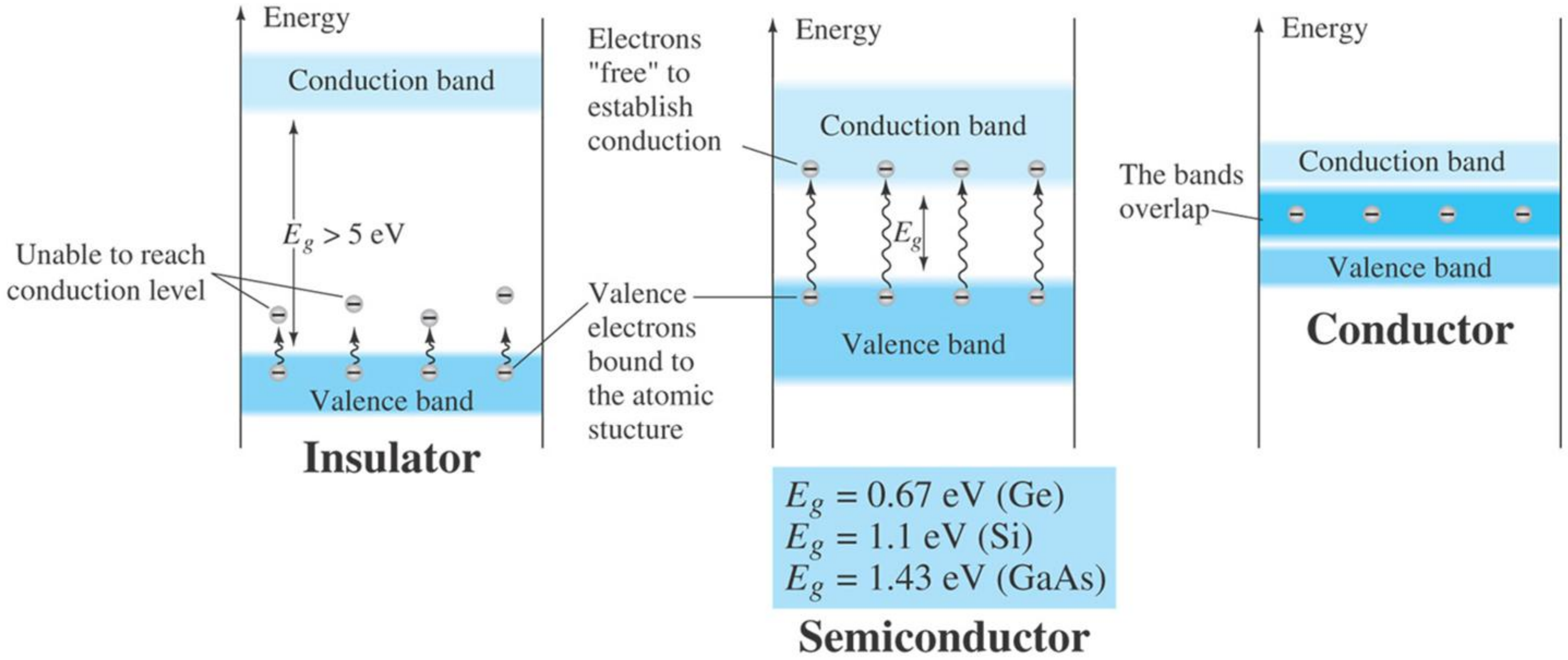
Energy Levels



(a)

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

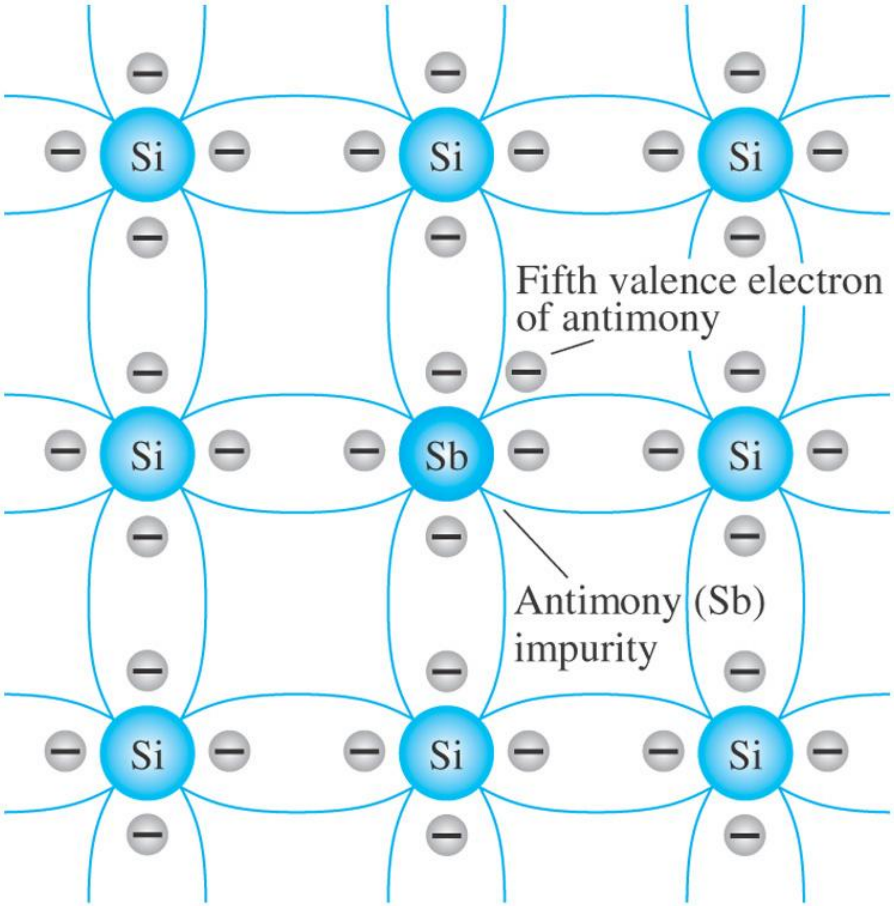
Energy Levels



An electron in the valence band of silicon must absorb more energy than one in the valence band of germanium to become a free carrier. [free carriers are free electrons due only to external causes such as applied electric fields established by voltage sources or potential difference.

n-Type and p-Type materials

n-Type Material

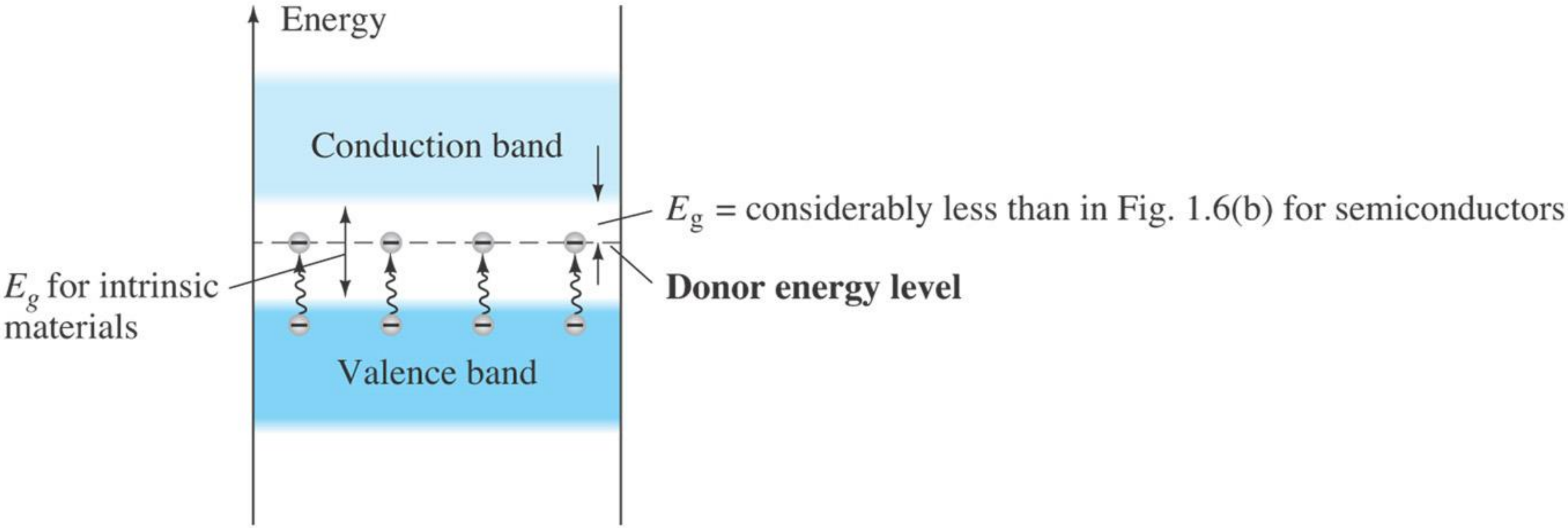


Doping with Sb, (antimony)

- n-Type materials are created by adding elements with **five** valence electrons such as antimony, arsenic, and phosphorous.
- There is a fifth electron due to the (Sb) atom that is relatively free to move in the n-Type material.
- The atoms (in this case is antimony (Sb)) are called **donor atoms.**

n-Type and p-Type materials

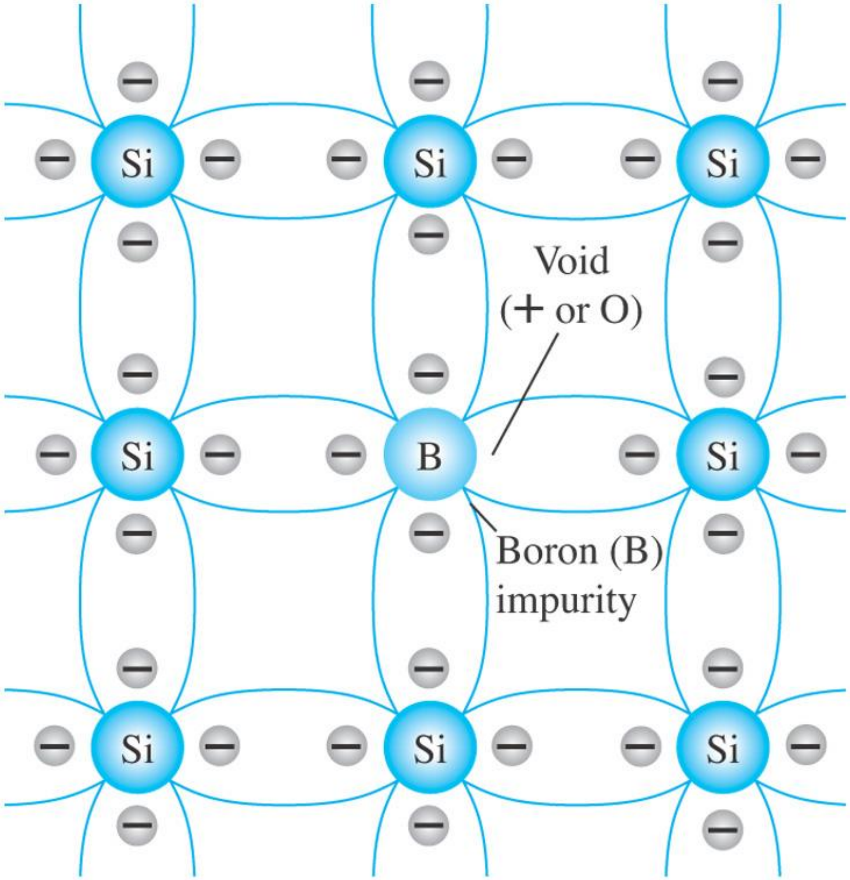
n-Type Material



The free electrons due to the added atoms have higher energy levels and require less energy to move to conduction band.

n-Type and p-Type materials

p-Type Material



Boron (B)

- p-Type materials are created by adding atoms with **three** valence electrons such as boron, gallium, and indium.
- In this case, an insufficient number of electrons to complete the covalent bonds.
- The resulting vacancy is called a "**hole**" represented by small circle or plus sign indicating absence of a negative charge.
- The atoms (in this case boron(B)) are called **acceptor atoms**.

Majority and Minority carriers

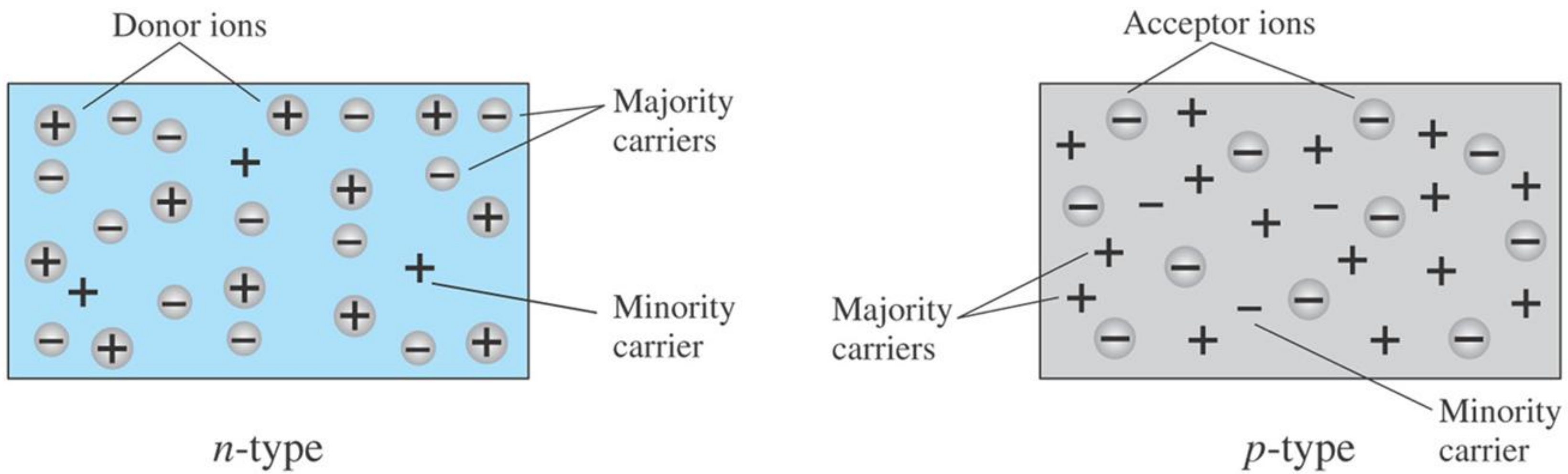
Two currents through a diode:

Majority Carriers

- The majority carriers in n-type materials are electrons.
- The majority carriers in p-type materials are holes.

Minority Carriers

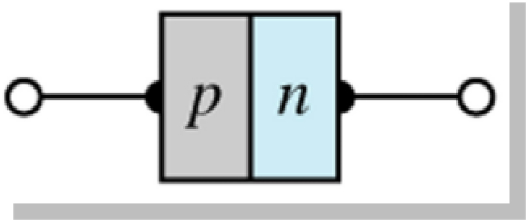
- The minority carriers in n-type materials are holes.
- The minority carriers in p-type materials are electrons.



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.

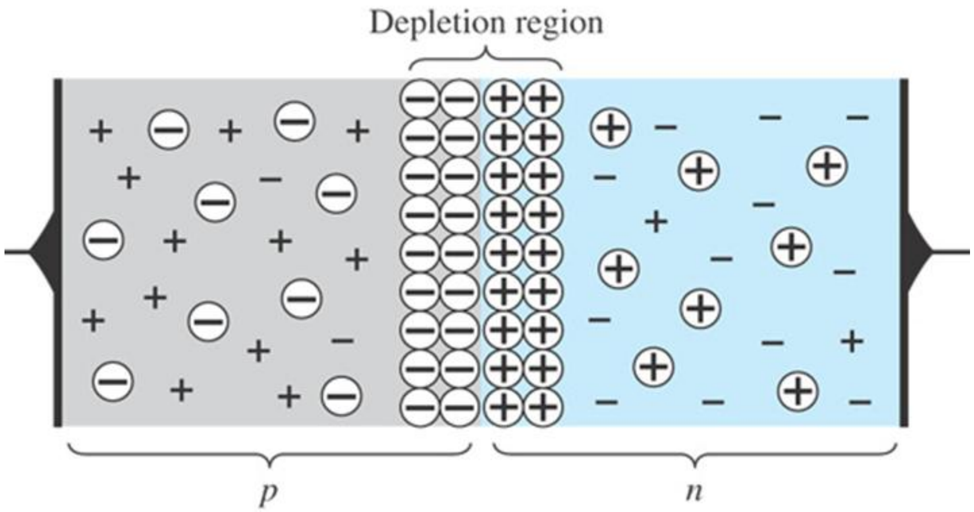


p-n Junctions

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).

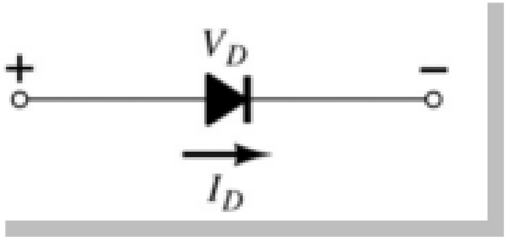
The electron migration results in a negative charge on the p-type side of the junction and a positive charge on the n-type side of the junction.



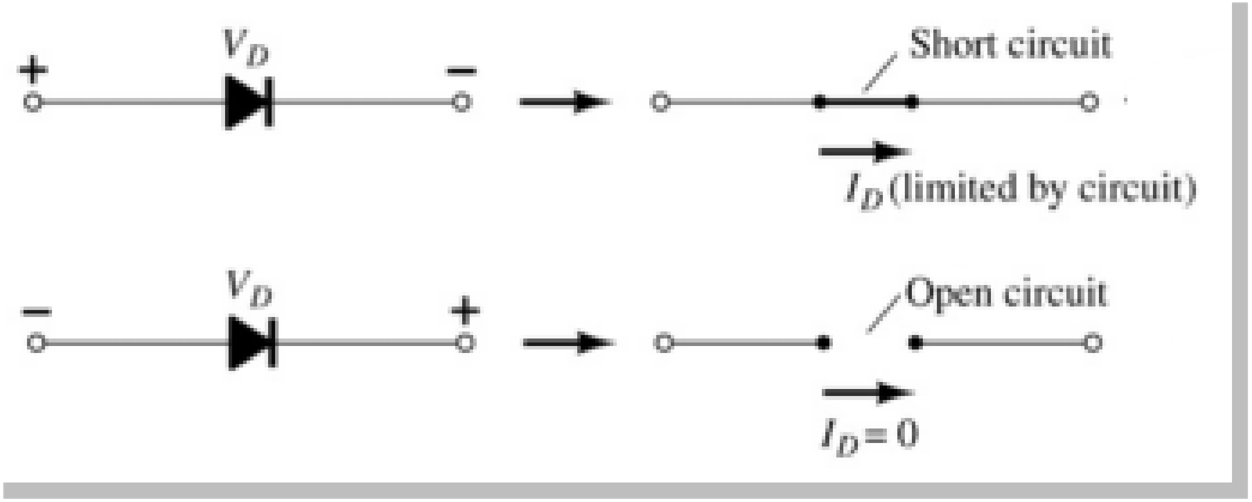
The result is the formation of a depletion region around the junction.

Diodes

The diode is a 2-terminal device.



A diode ideally conducts in only one direction.

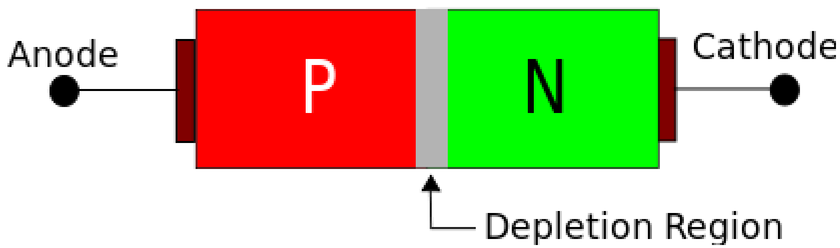


Electronic Devices and Circuit Theory, 10/e
Robert L. Boylestad and Louis Nashelsky

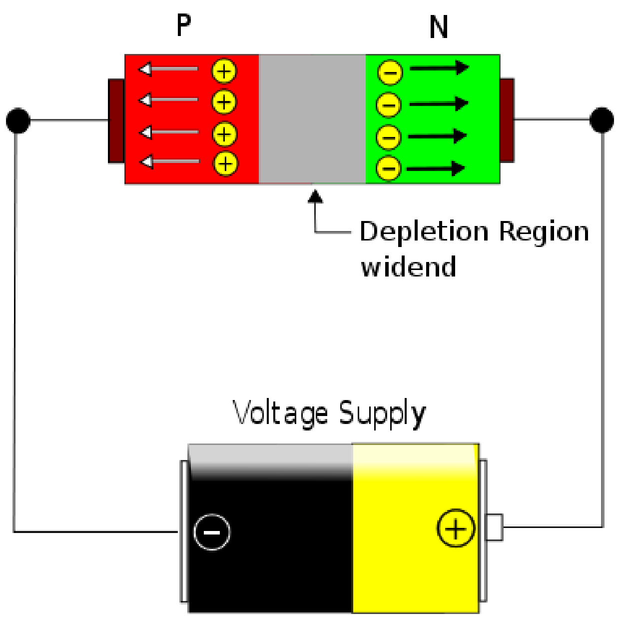
Diode Operating Conditions

- No bias
- Forward bias
- Reverse bias

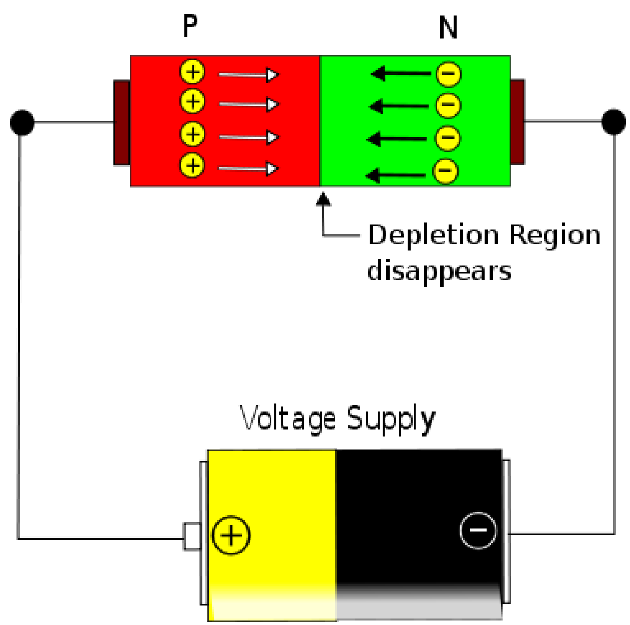
Semiconductor Diode Construction



Reverse bias

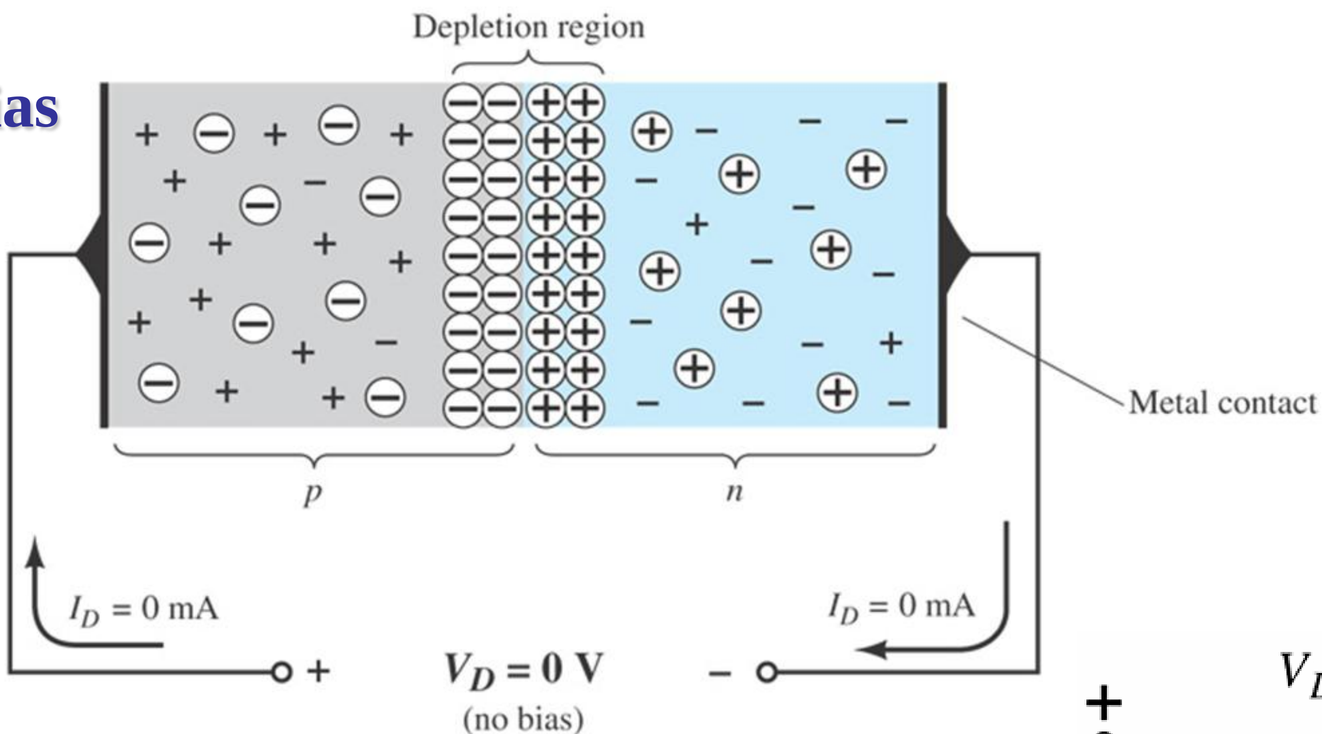


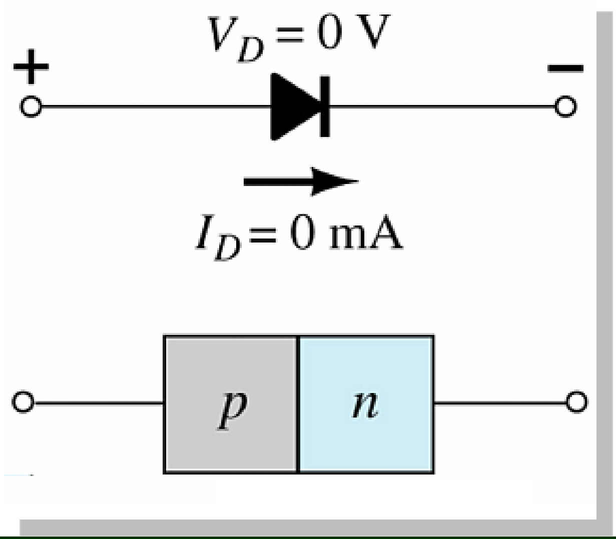
Forward bias



Diode Operating Conditions

No Bias



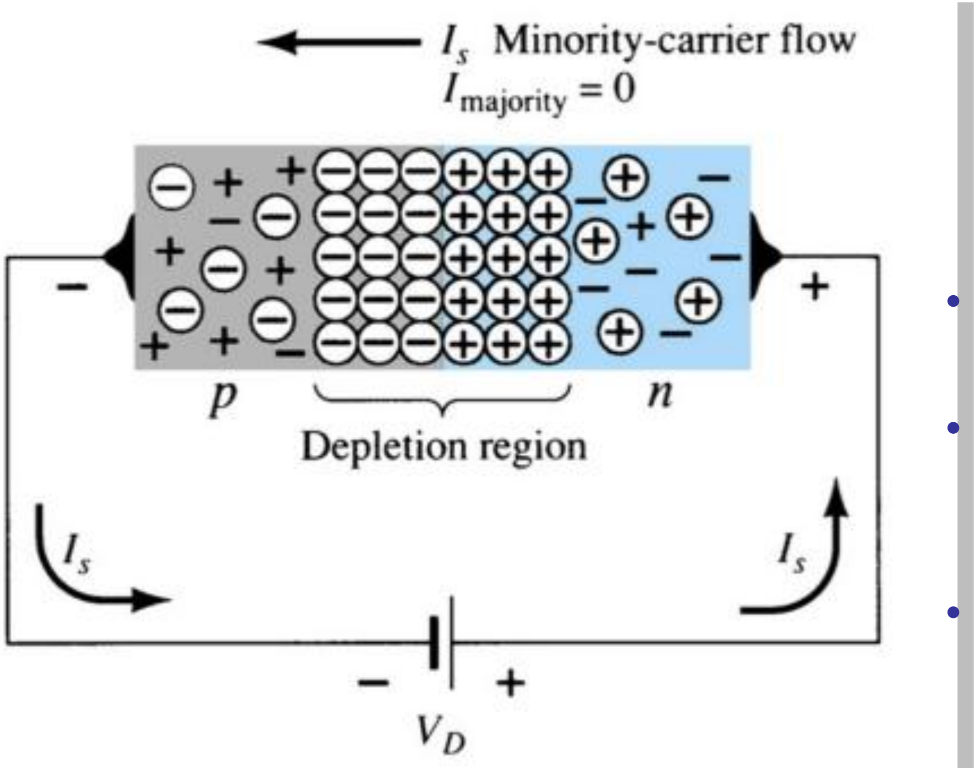


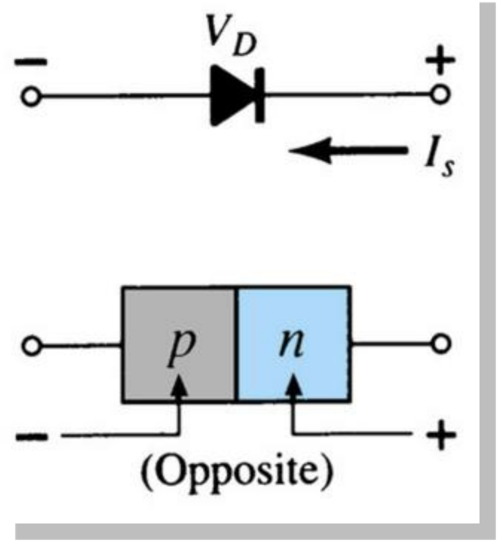
- **No external voltage is applied: $V_D = 0$ V**
- **No current is flowing: $I_D = 0$ A**
- **Only a modest depletion region exists**

Diode Operating Conditions

Reverse Bias

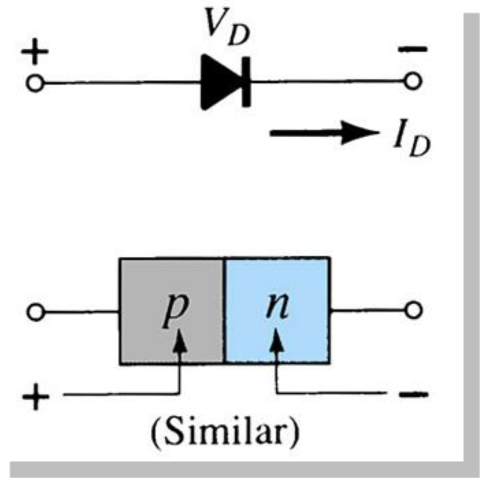
External voltage is applied across the *p-n* junction in the opposite polarity of the *p-* and *n*-type materials.





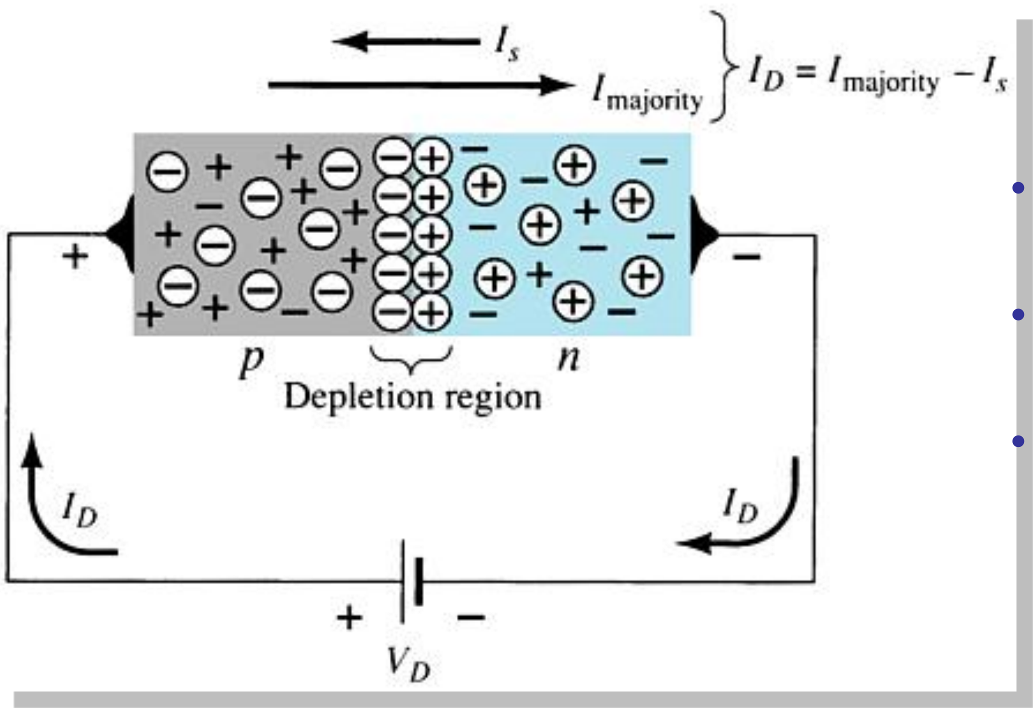
- **The reverse voltage causes the depletion region to widen.**
- **The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

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.



- **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.**

Actual Diode Characteristics

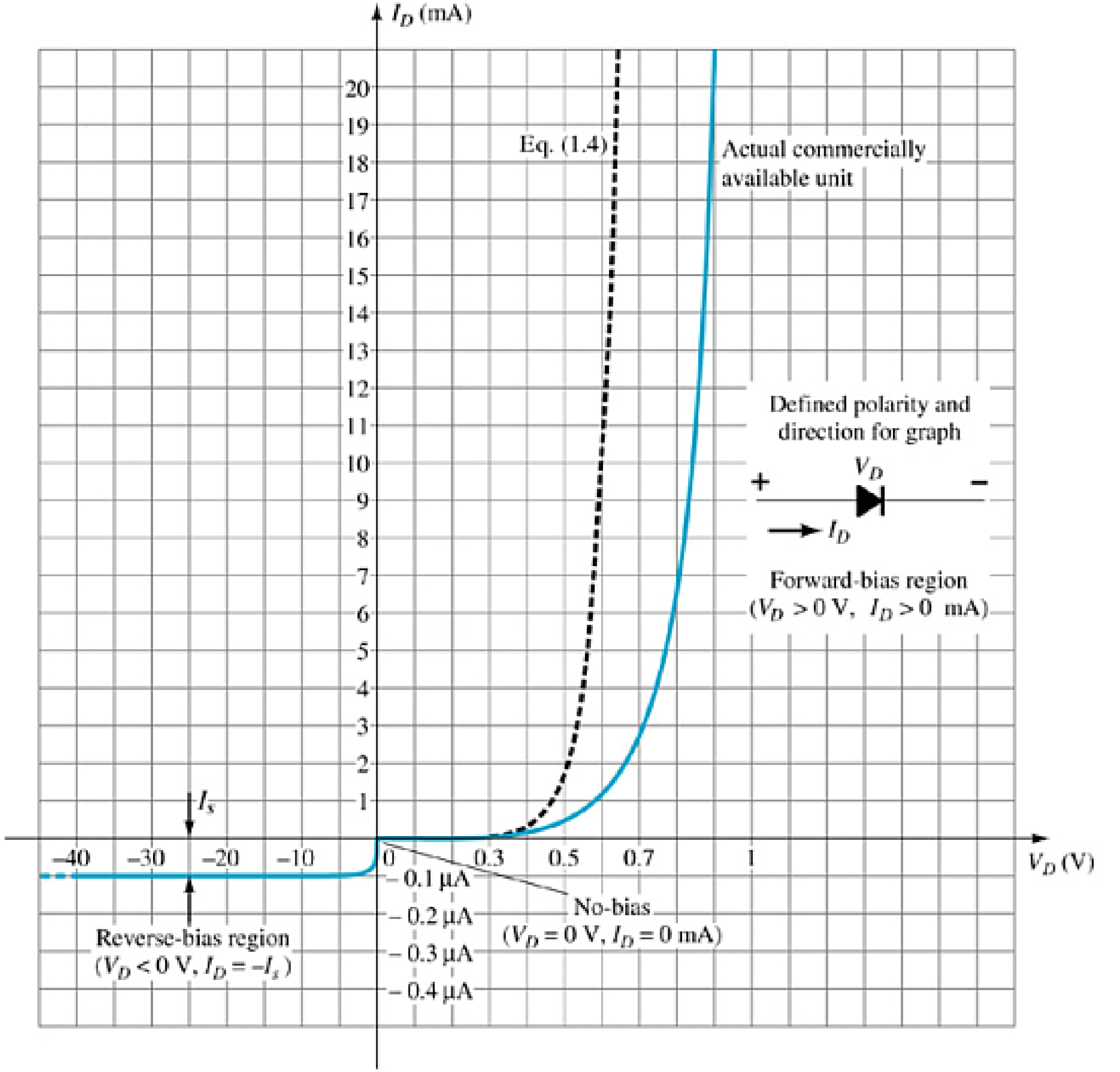
Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.

The reverse saturation current is seldom more than a few microamperes.

$$I_D = I_S\left(e^{V_D/nV_T} - 1\right)$$

$$V_T = \frac{kT}{q}$$



Diode equation

$$I_D = I_S\left(e^{V_D/nV_T} - 1\right)$$

$$V_T = \frac{kT}{q}$$

where

$\boldsymbol{V_T}$: is called the thermal voltage.

$\boldsymbol{I_s}$: is the reverse saturation current.

$\mathbf{V_D}$: is the applied forward-bias voltage across the diode.

n : is a factor function of operation conditions and physical construction. It has range between 1 and 2. assume n=1 unless otherwise noted.

K : is Boltzman's constant =1.38 x 10^{-23}

T: is temperature in kelvins = 273+temperature in C.

q : is the magnitude of electron charge = 1.6 x 10^{-19} C.