Semiconductor Manufacturing Technology

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Chapter 2

Characteristics of Semiconductor Materials

Objectives

After studying the material in this chapter, you will be able to:

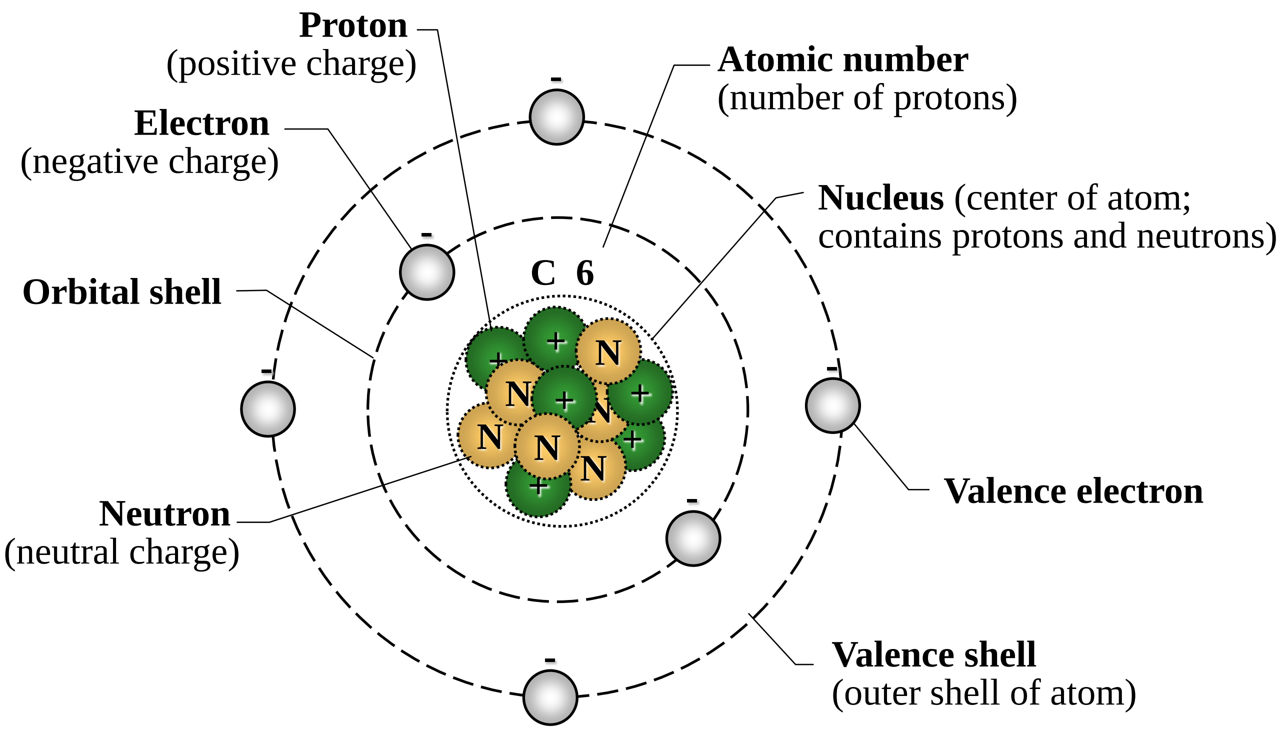
1. Describe the atom, including valence shell, band theory and ions.
2. Interpret the periodic table with regards to main group elements and explain how ionic and covalent bonds are formed.
3. State the three classes of materials and describe each one with regards to current flow.
4. Explain resistivity, resistance, capacitance and discuss their importance to wafer fabrication.
5. Describe pure silicon and give four reasons why it is the most common semiconductor material.
6. Explain doping and how the trivalent and pentavalent dopant elements make silicon a useful semiconductor material.
7. Explain p-type (acceptor) silicon and n-type (donor) silicon, how silicon resistivity changes with the addition of a dopant, and the PN junction.
8. Discuss alternative semiconductor materials, with emphasis on gallium arsenide.

Atomic Structure

- Matter
- Element
  - Nucleus
    - Proton
    - Neutron
  - Orbital Shell
    - Electron
- Molecule
- Compound (substance different from individual)

- Electrons
  - Electron Energy
  - Valence Shells
  - Energy-Band Theory
  - Ions

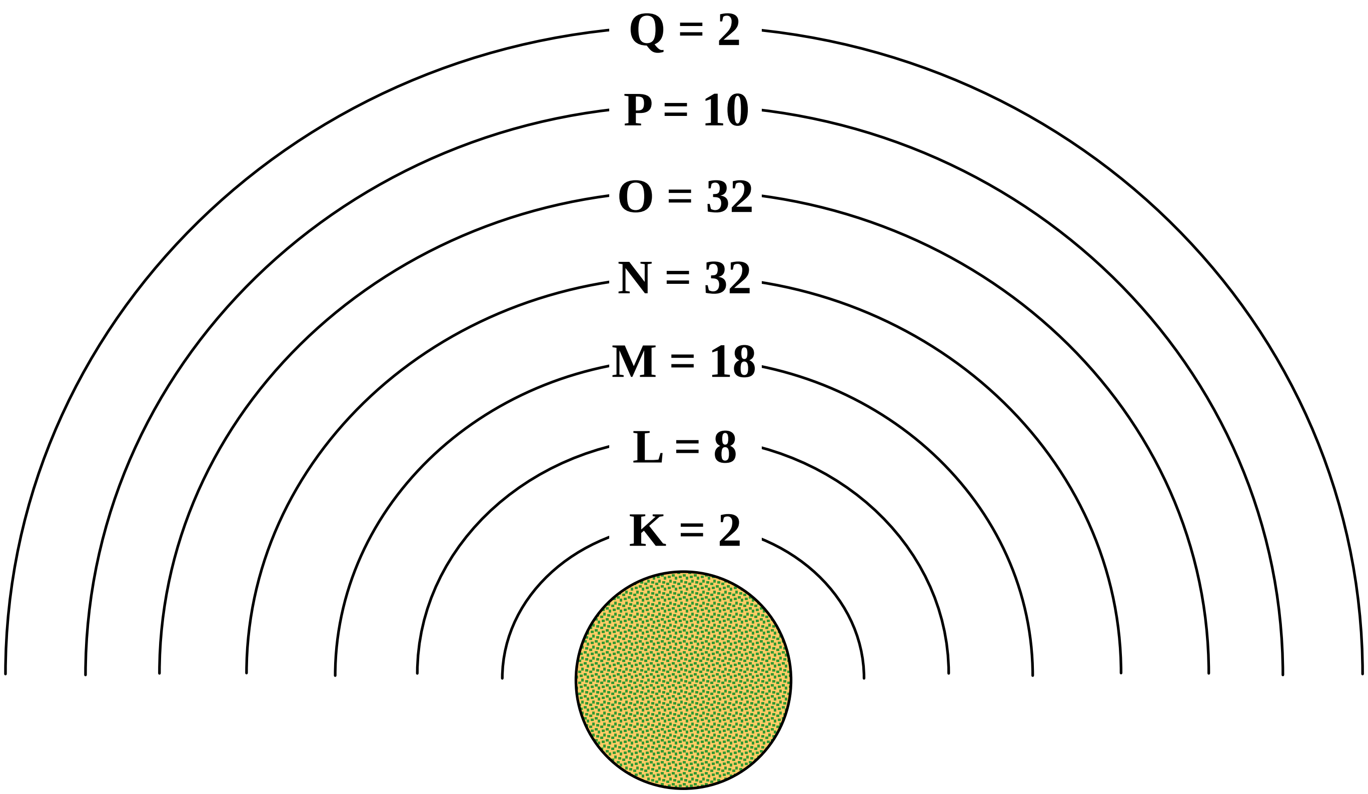
Elementary Model of the Carbon Atom



Carbon atom: The nucleus contains an equal number of protons (+) and neutrons (6 each). Six electrons (-) orbit around the nucleus.

Figure 2.1

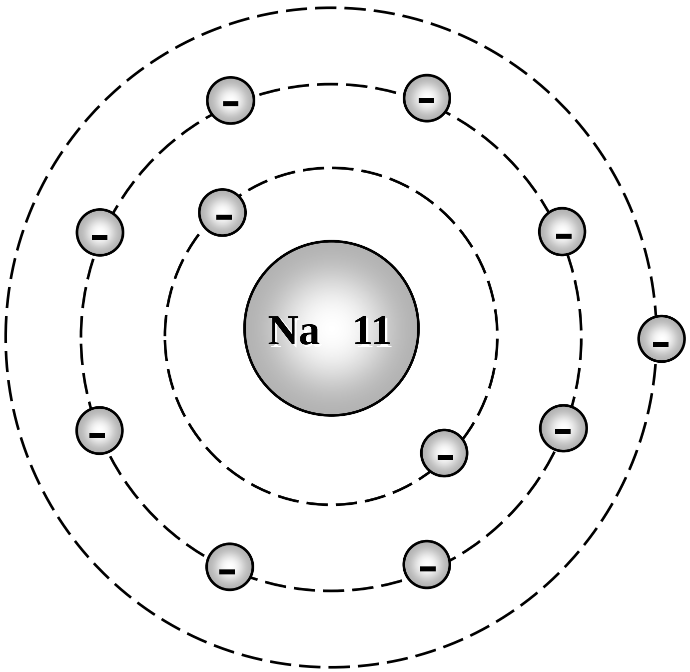
Electron Shells in Atoms



Electron energy (eV): the kinetic energy gain by a electron in passing a 1V potential gap.

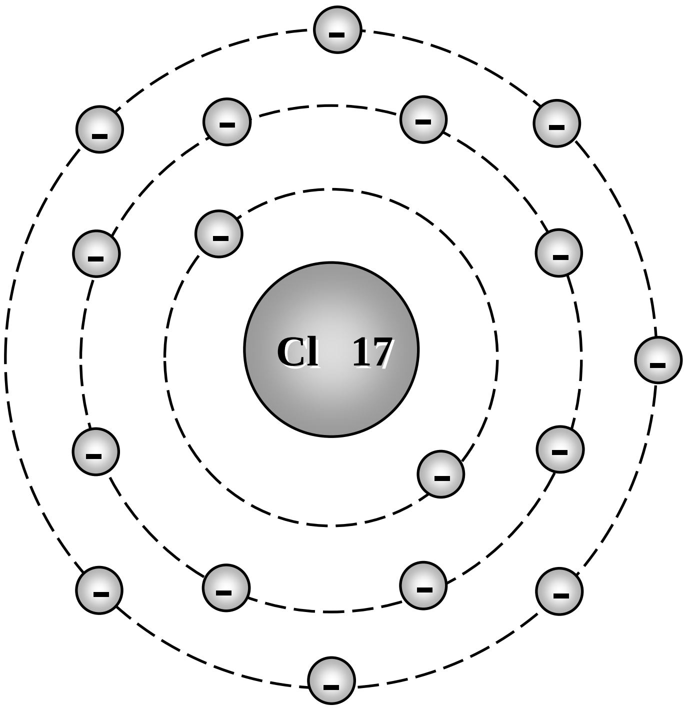
Figure 2.2

Electron Shells for Sodium and Chlorine Atoms



Sodium atom

Easy to give up a electron



Chlorine atom

It has an affinity to accept one electron

Figure 2.3

Energy Band Gaps

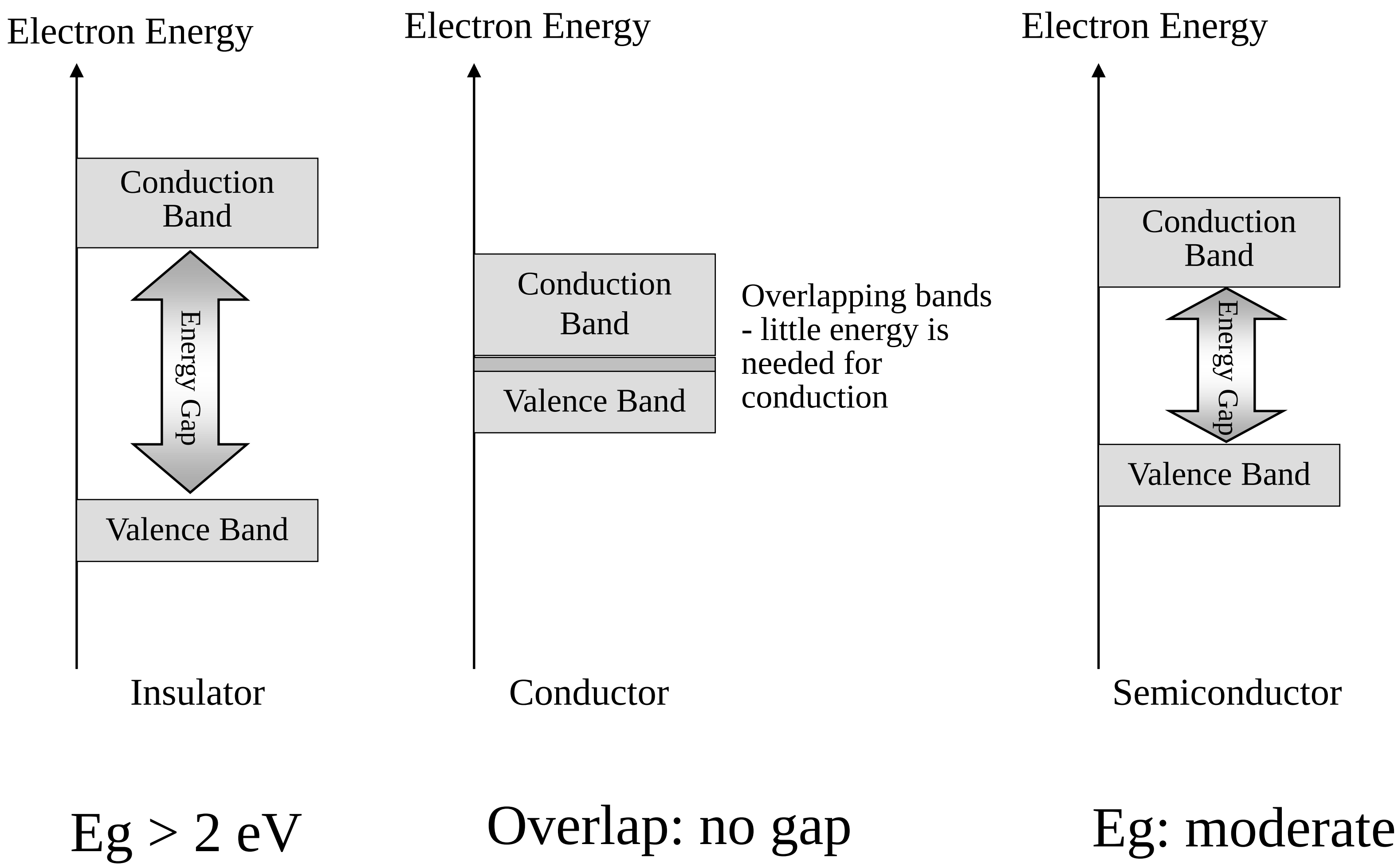
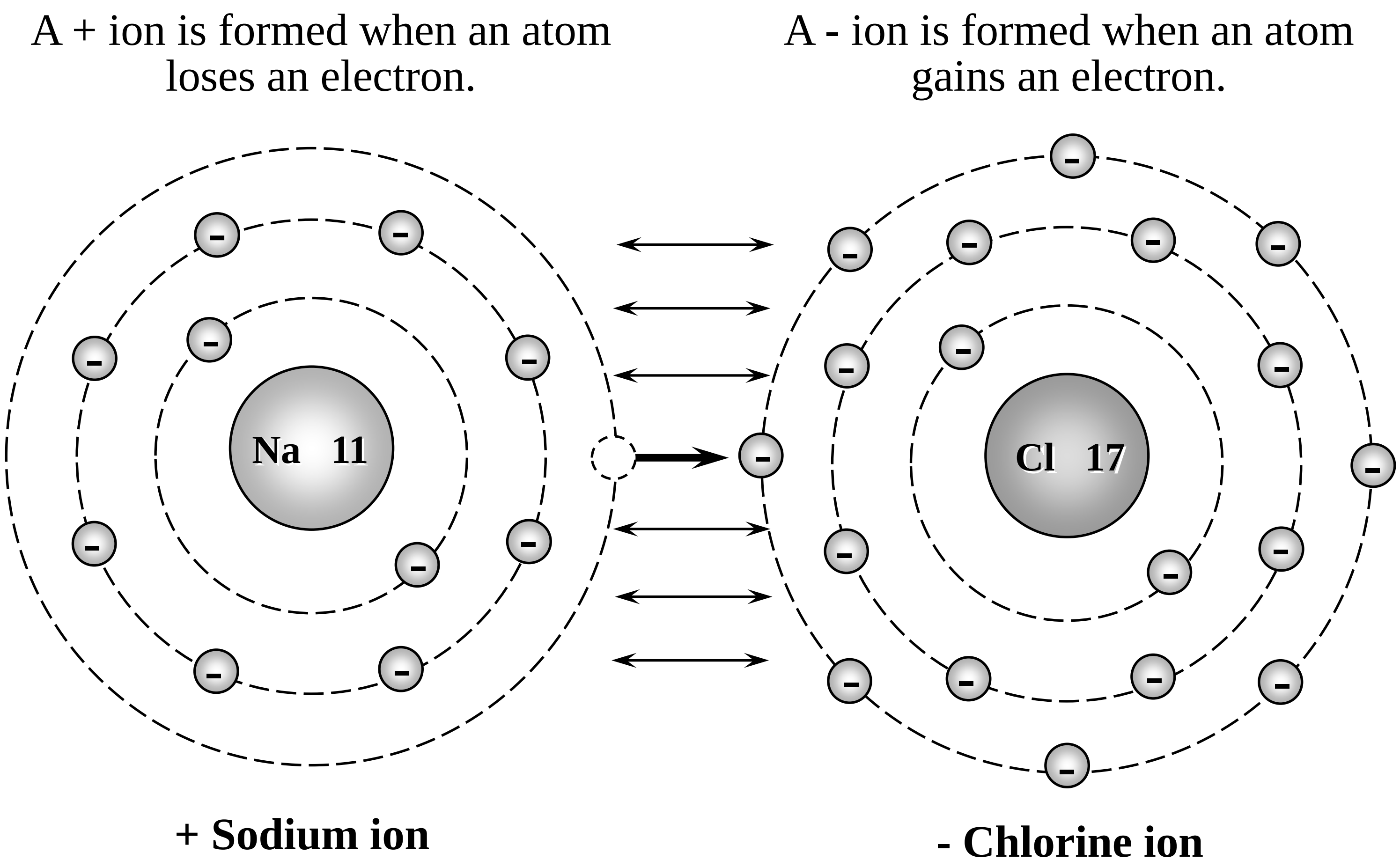


Figure 2.4

Sodium Chloride: ionic compound



• **Once gas particles are charged by ionization, the gas flow and motion of atoms can be controlled by use of electrostatic and magnetic fields.**

Figure 2.5

The Periodic Table

- Characteristics of Commonly Used Elements
- Ionic Bonds
- Covalent Bonds

The Periodic Table of the Elements

Transition Metals

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 1.008 H Hydrogen																	2 4.0026 He Helium
3 6.939 Li Lithium	4 9.012 Be Beryllium											5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Florine	10 20.183 Ne Neon
11 22.989 Na Sodium	12 24.312 Mg Magnesium											13 26.981 Al Aluminum	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.064 S Sulfur	17 35.453 Cl Chlorine	18 39.948 Ar Argon
19 39.102 K Potassium	20 40.08 Ca Calcium	21 44.956 Sc Scandium	22 47.90 Ti Titanium	23 50.942 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.847 Fe Iron	27 58.933 Co Cobalt	28 58.71 Ni Nickel	29 63.54 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.922 As Arsenic	34 78.96 Se Selenium	35 79.909 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.905 Y Yttrium	40 91.22 Zr Zirconium	41 92.906 Nb Niobium	42 95.94 Mo Molybde- num	43 99 Tc Technitium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.4 Pd Palladium	47 107.87 Ag Silver	48 112.40 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.904 I Iodine	54 131.30 Xe Xenon
55 132.90 Cs Cesium	56 137.34 Ba Barium	57 138.91 La Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.2 Re Rhenium	76 190.2 Os Osmium	77 192.2 Ir Iridium	78 195.09 Pt Platinum	79 196.967 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 210 Po Polonium	85 210 At Astatine	86 222 Rn Radon
87 223 Fr Francium	88 226 Ra Radium	89 227 Ac Actinium	104 Rf	105 Ha	106 Sg	107 Uns	108 Uno	109 Une	110 Uun								

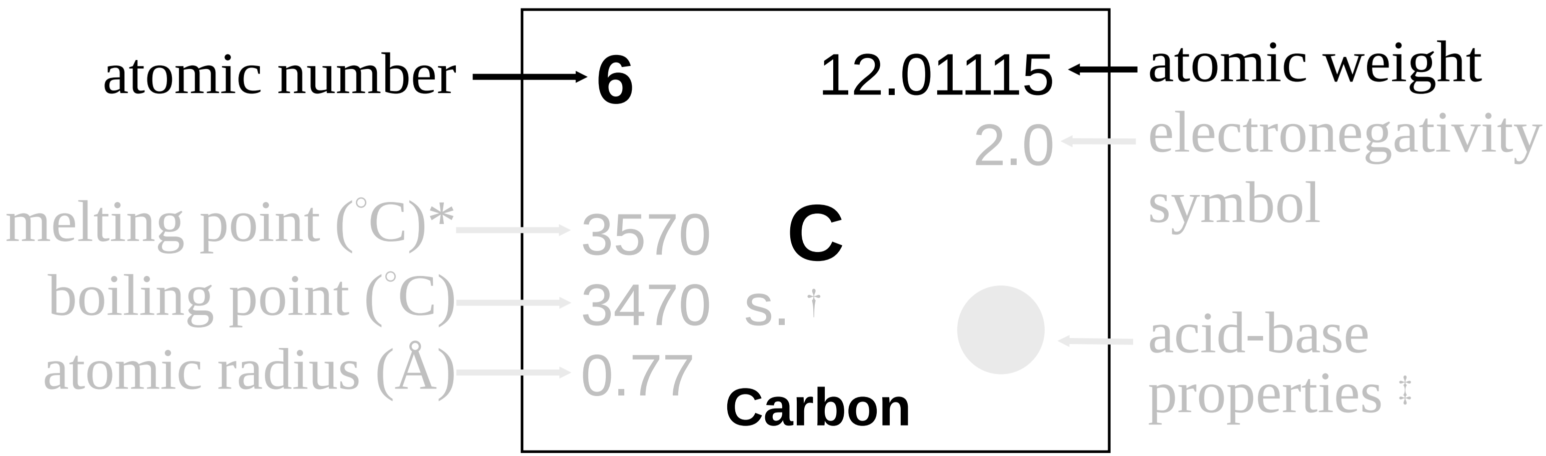
Nonmetals

Metalloids (semimetals)

Lanthanides	58 140.12 Ce Cerium	59 140.91 Pr Praseodym- ium	60 144.24 Nd Neodym- ium	61 147 Pm Prome- thium	62 150.35 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolin- ium	65 158.92 Tb Terbium	66 162.50 Dy Dyspro- sium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
Actinides	90 232.04 Th Thorium	91 231 Pa Procat- inium	92 238.03 U Uranium	93 237 Np Neptunium	94 242 Pu Plutonium	95 243 Am Americium	96 247 Cm Curium	97 247 Bk Berkelium	98 249 Cf Califor- nium	99 254 Es Einstein- ium	100 253 Fm Fermium	101 256 Md Mendelev- ium	102 253 No Nobelium	103 257 Lr Lawren- cium

Figure 2.6

Element Box of the Periodic Table



* Based on carbon-12. ( ) indicates the most stable or best known isotope.

† s. indicates sublimation

‡ For representative oxides of group. Oxide is acidic if color is red, basic if color is blue, and amphoteric if both colors are shown. Intensity of color indicates relative strength.

Figure 2.7

Characteristics of Chemicals used in Wafer Fabrication

Group Number	Characteristics
IA	• 1 valence electron that is easily given up; low electronegativity • Highly unstable • Very reactive; explosive • Forms ionic bonds • Prefer not to use the metals in this group due to **contamination** issues
IIA	• 2 valence electrons • Somewhat unstable • Quite reactive • Prefer not to use metals in this group
IIIA	• 3 valence electrons • **Dopant elements (primarily B**) added to semiconductor material • Common interconnect conductor material (Al)
IVA	• 4 valence electrons • **Semiconductor** materials • Forms **covalent bonds**

Continued on next slide ⇨

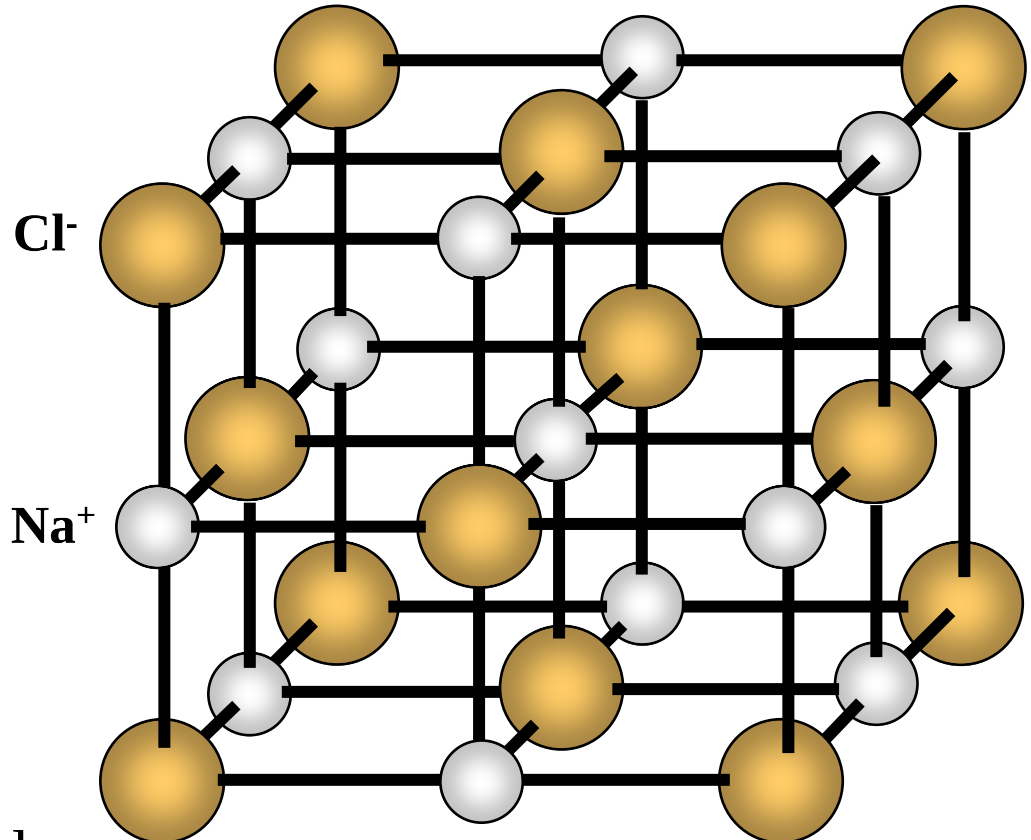
Table 2.1

Characteristics of Chemicals used in Wafer Fabrication (continued)

Group Number	Characteristics
VA	• 5 valence electrons • **Dopant** elements (primarily P and As)
VIA	• 6 valence electrons
VIIA	• 7 valence electrons; readily accepts electrons; **high electronegativity** • Corrosive • Very reactive • Forms ionic bonds • Useful in some semiconductor application; dangerous etching and cleaning compounds
VIIIA	• 8 valence electrons • Stable; **nonreactive** • **Inert** gas • Safe to use in semiconductor manufacturing
IB	• **Best metal conductors** • Cu is replacing Al as primary interconnect conductor material
IVB – VIB	• **Refractory** (high melting temperature) metals commonly used in semiconductor manufacturing to improve metallization (especially Ti, W, Mo, Ta, and Cr) • Reacts well with silicon to form stable compound with good electrical characteristics

Table 2.1

Ionic Bond for NaCl



Formation of ionic bonds

- Oxidation: loss of electrons (Na^+)
- Reduction: gain of electrons (Cl^-)

Figure 2.8

Covalent Bond for HCl

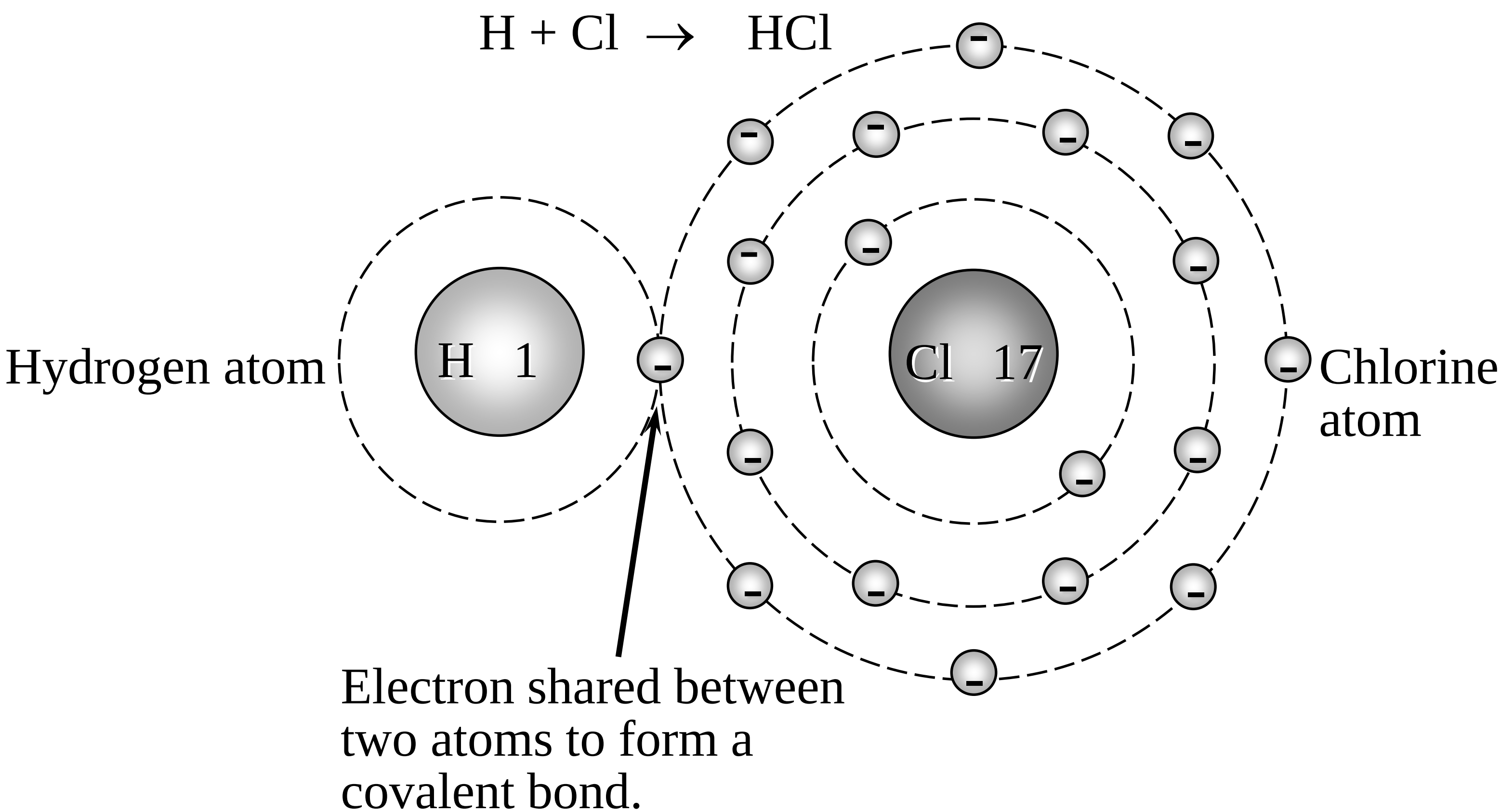


Figure 2.9

Classifying Materials

- Conductors
- Insulators
- Semiconductors

Electrical Current Flow

Copper wires provide connections that allow electrons to flow from the - terminal, through the filament inside the lamp, and back into the + terminal of the battery.

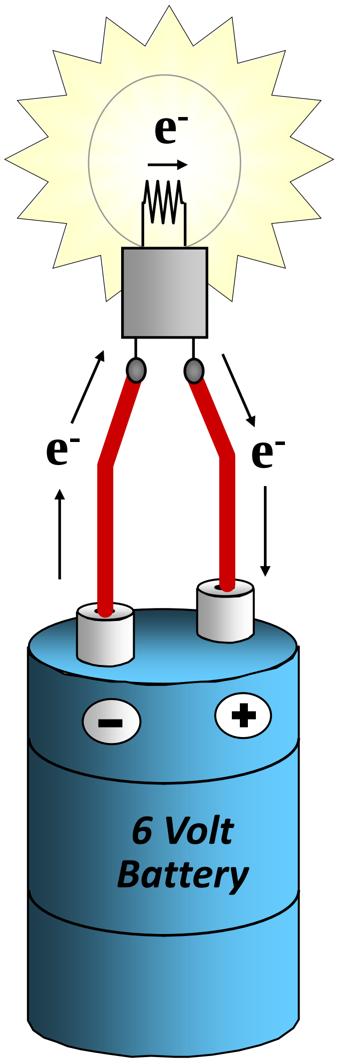


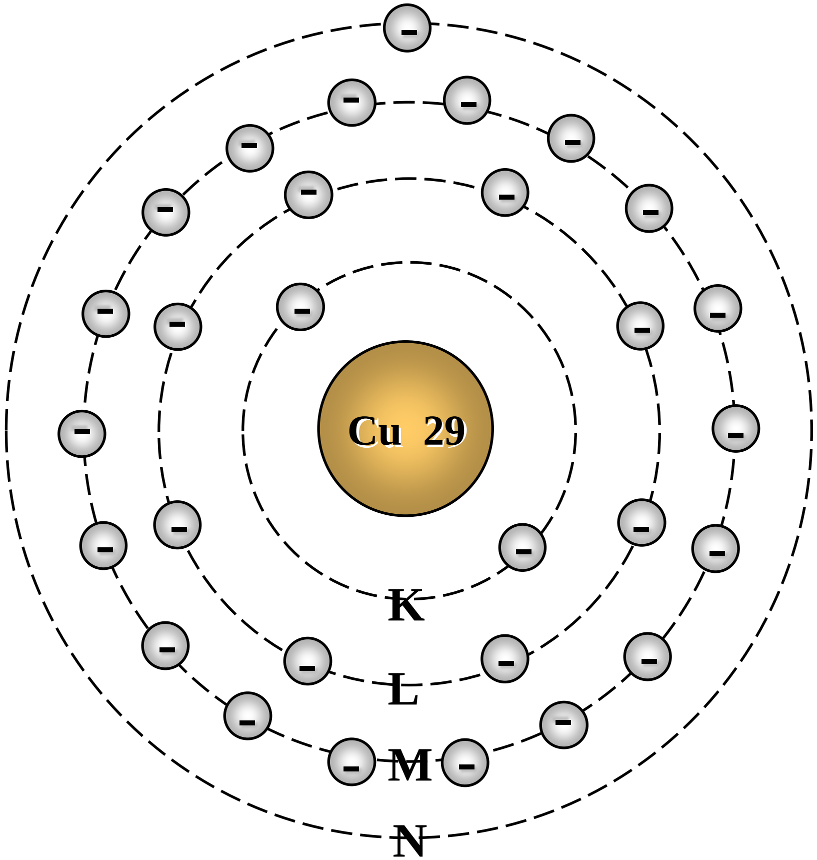
Figure 2.10

Flow of Free Electrons in Copper

Copper atom

Shell #	Maximum # e^- per shell	Actual # e^- per shell
K	2	2
L	8	8
M	18	18
N	32	1
Total #	**60**	**29**

One electron in the valence ring



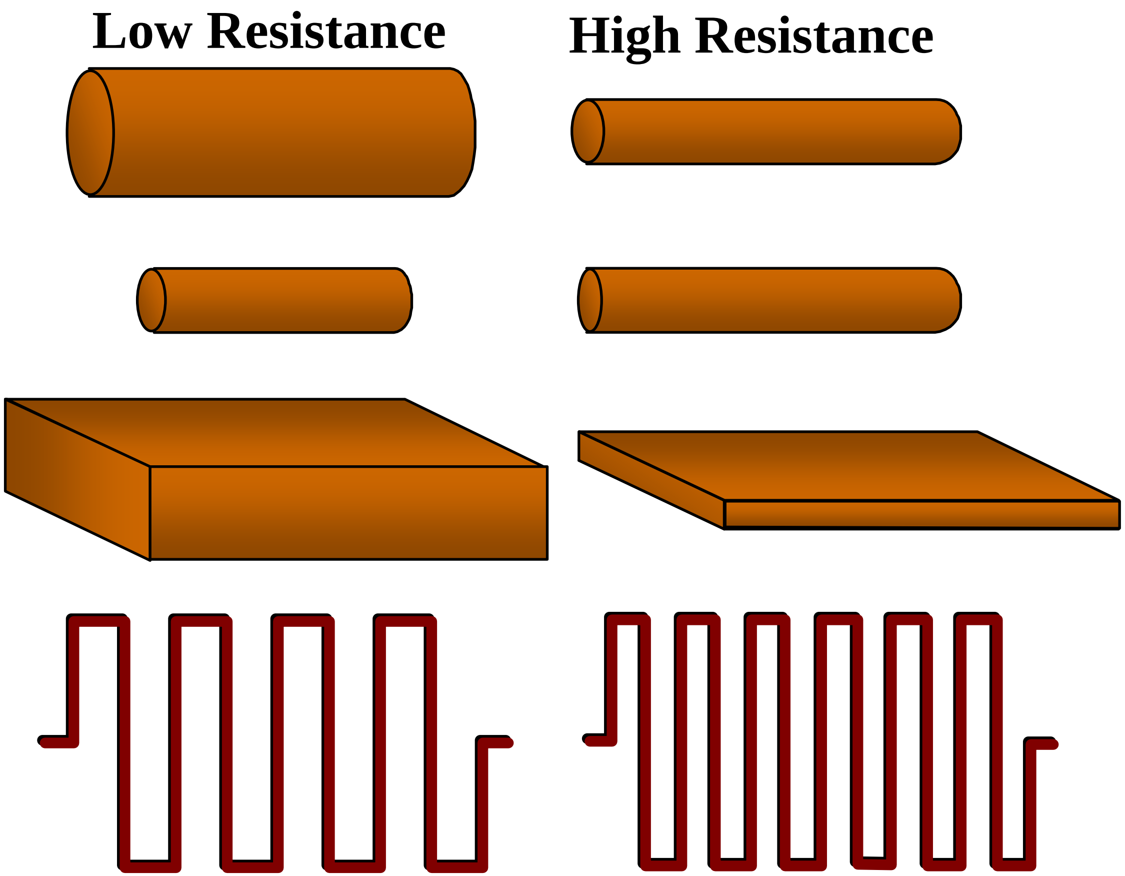
-In metal, for every conduction-band electron there must exist a valence-band hole (electron-hole pair)

-When electron gives up it energy and falls into the hole, called **recombination**. Time of this period is **lifetime.**

Figure 2.11

How Sizes Affect Resistance

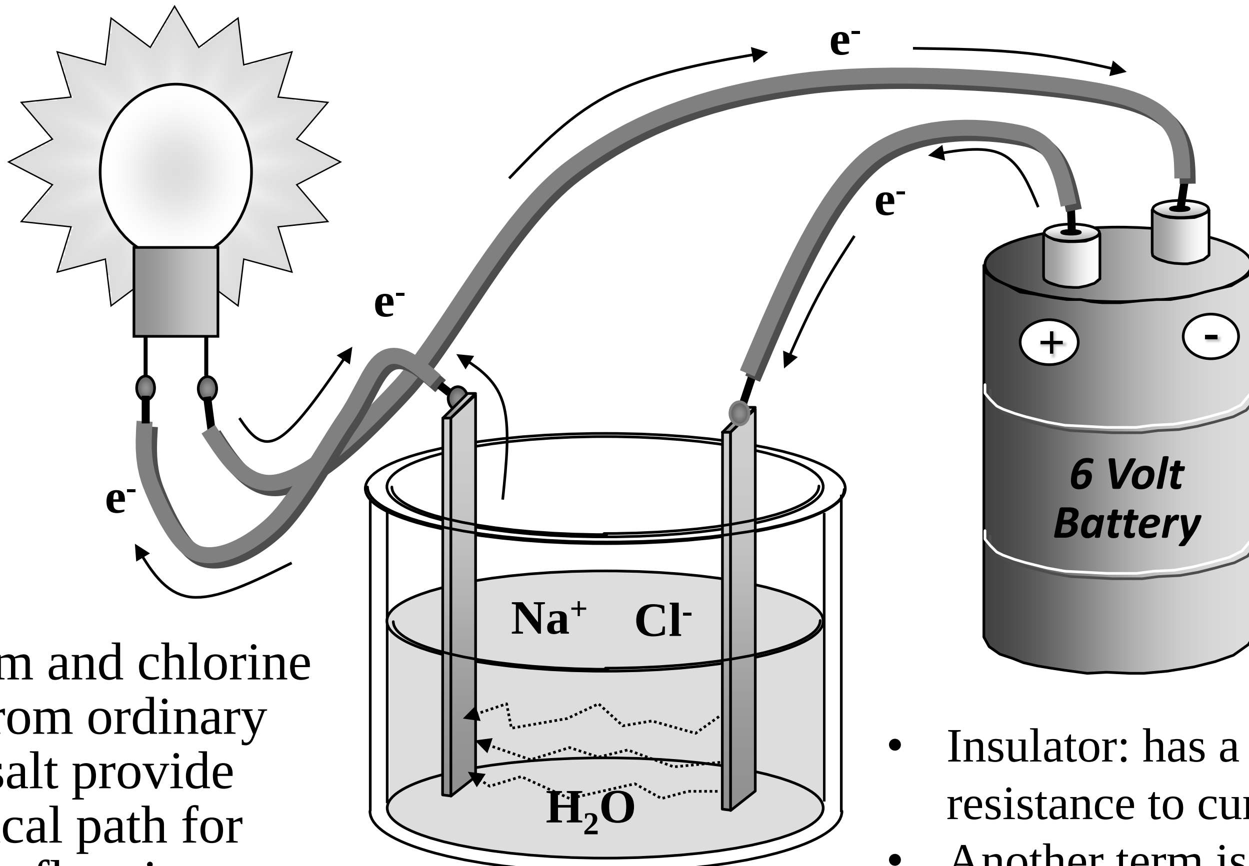
$$R = \frac{\rho L}{A}$$



<u>Resistance</u> is the opposition to current flow and is accompanied by the dissipation of heat

Figure 2.12

Adding an Impurity to Water to Improve its Conductivity

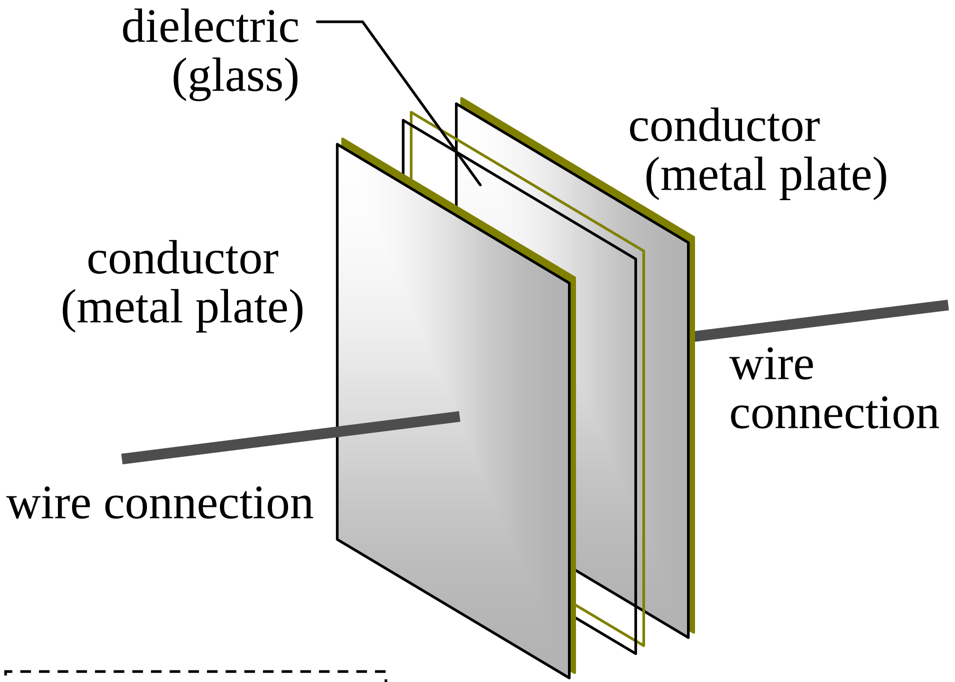


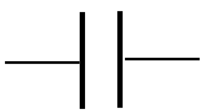
Sodium and chlorine ions from ordinary table salt provide electrical path for current flow in water.

- Insulator: has a high resistance to current flow
- Another term is dielectric

Figure 2.13

Basic Capacitor Structure
[Store charge]





Schematic symbol for Capacitor

Formula for Capacitance

$$C = \frac{KA}{S}$$

K, dielectric constant in farads/cm

A, plate area in cm^2

S, spacing between plates in cm

Figure 2.14

Battery Charges a Capacitor

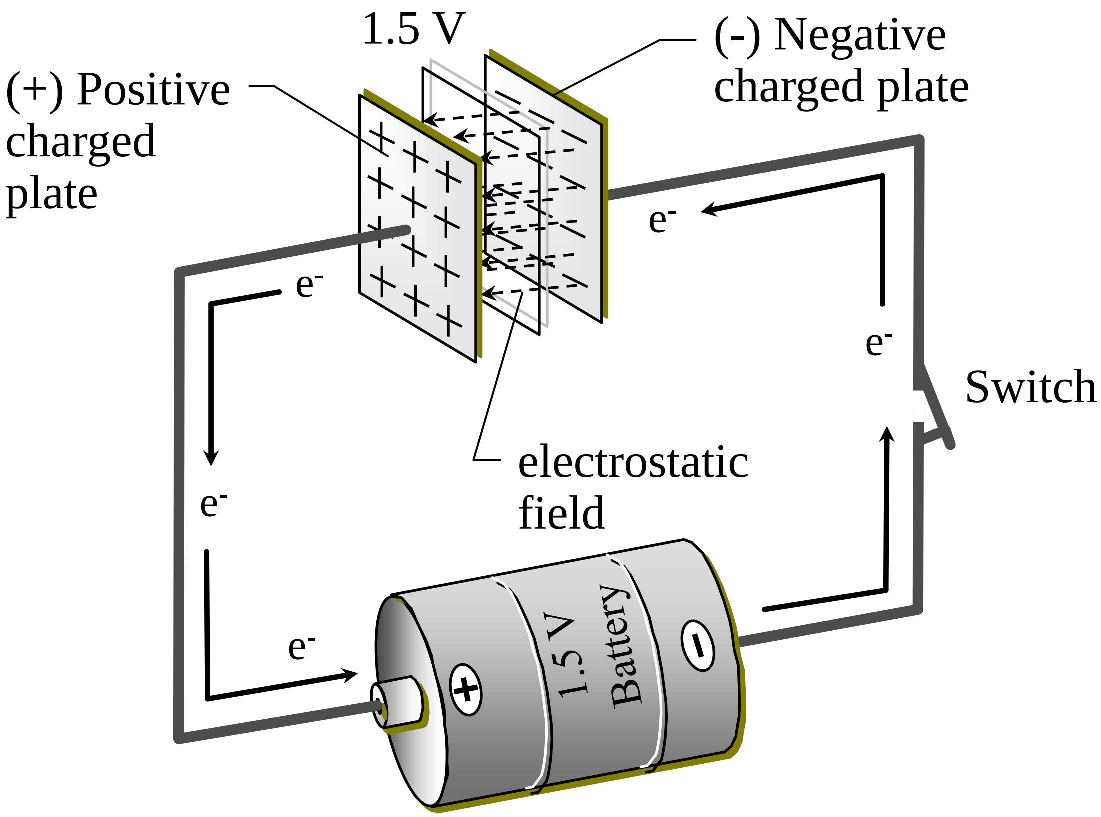


Figure 2.15

Capacitor Holds a Charge

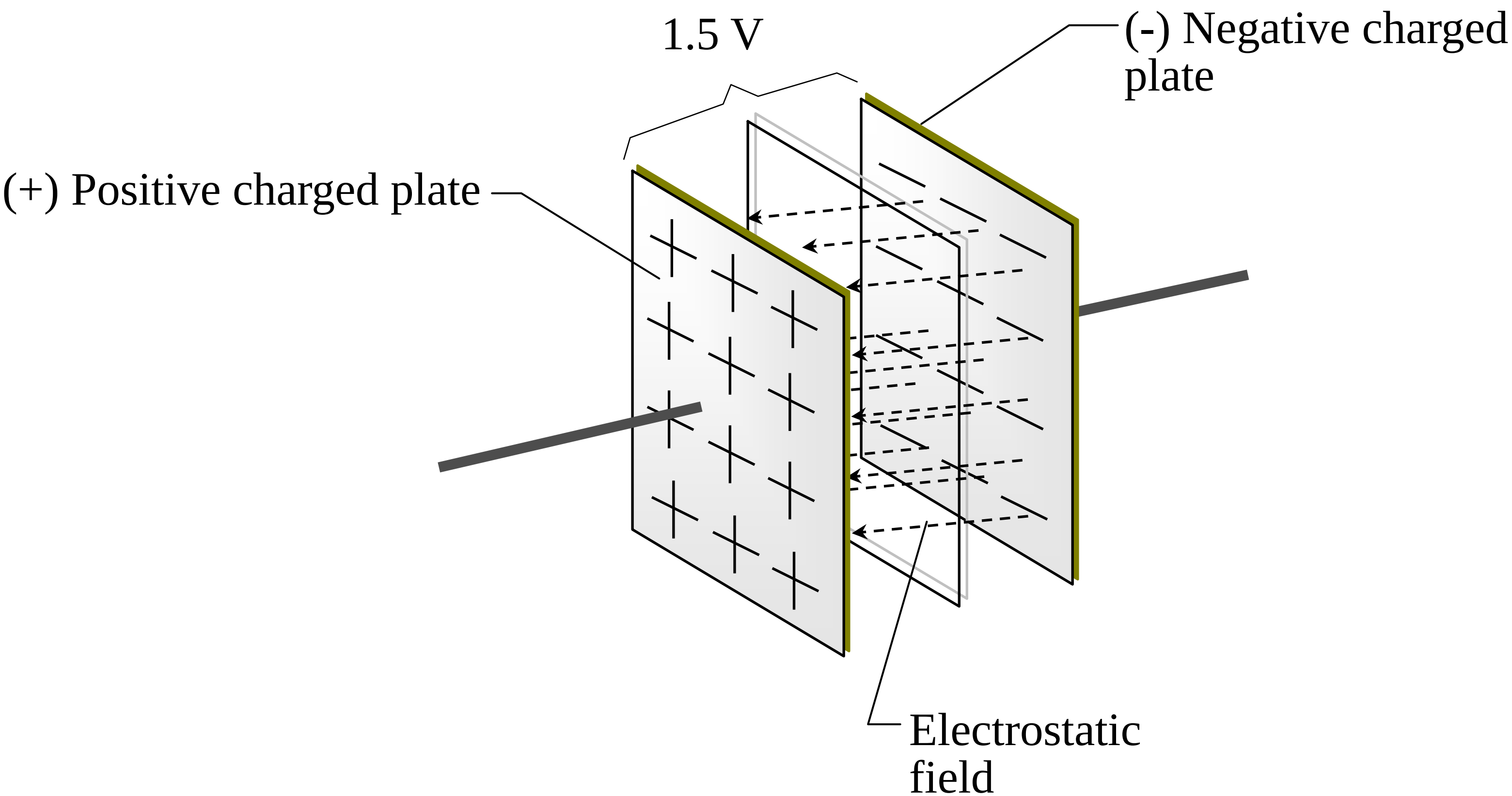
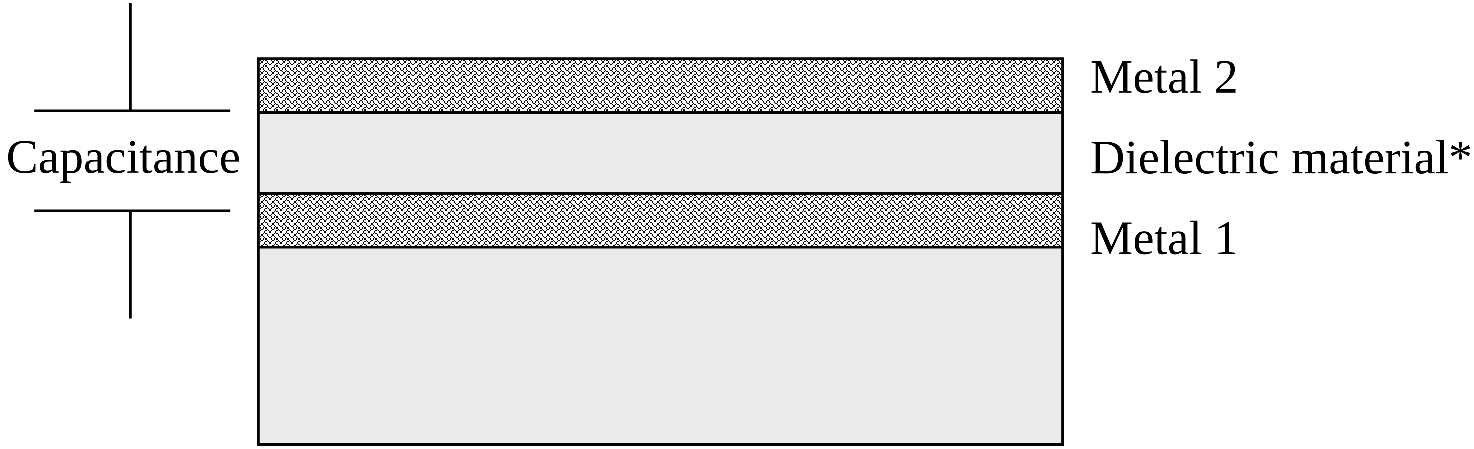


Figure 2.16

Low-*k* Dielectric Material



- *Low k dielectric reduces capacitance between metal layers.*
- *High k dielectric increases C for devices and memory.*

Figure 2.17

Silicon

- Pure Silicon
- Why Use Silicon?
- Doped Silicon
  - Dopant Materials
  - n-type Silicon
  - p-type Silicon
  - Resistivity of Doped Silicon
- pn Junctions

Group IVA Elemental Semiconductors

Semiconductors

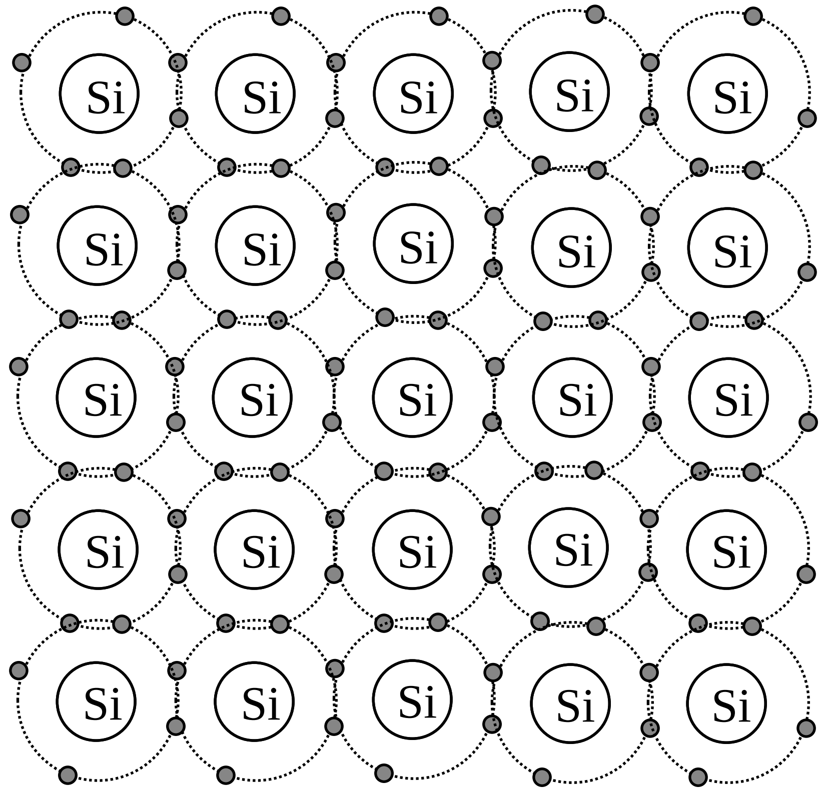
Group IVA	
C, Carbon	6
Si, Silicon	14
Ge, Germanium	32
Sn, Tin	50
Pb, Lead	82

Semiconductor: can be either conductor or insulator

Figure 2.18

Covalent Bonding of Pure Silicon

Silicon is not found pure in nature, it needs **refined** and **purified**

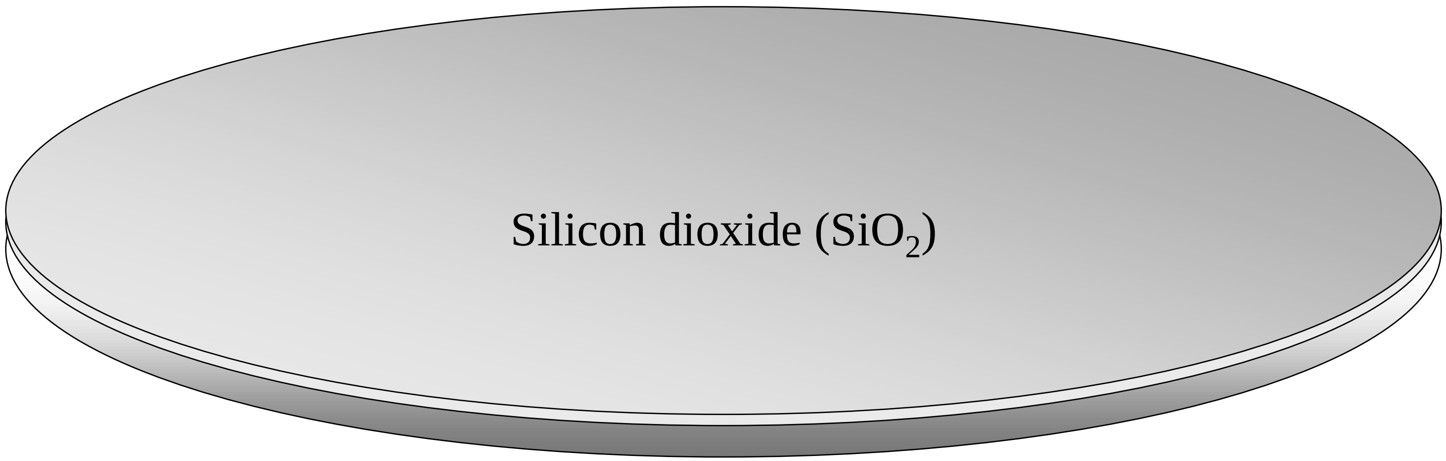


Silicon atoms share valence electrons
to form insulator-like bonds.

Pure silicon is a **poor conductor**, no free electron, no use.

Figure 2.19

SiO_2 on Silicon Wafer

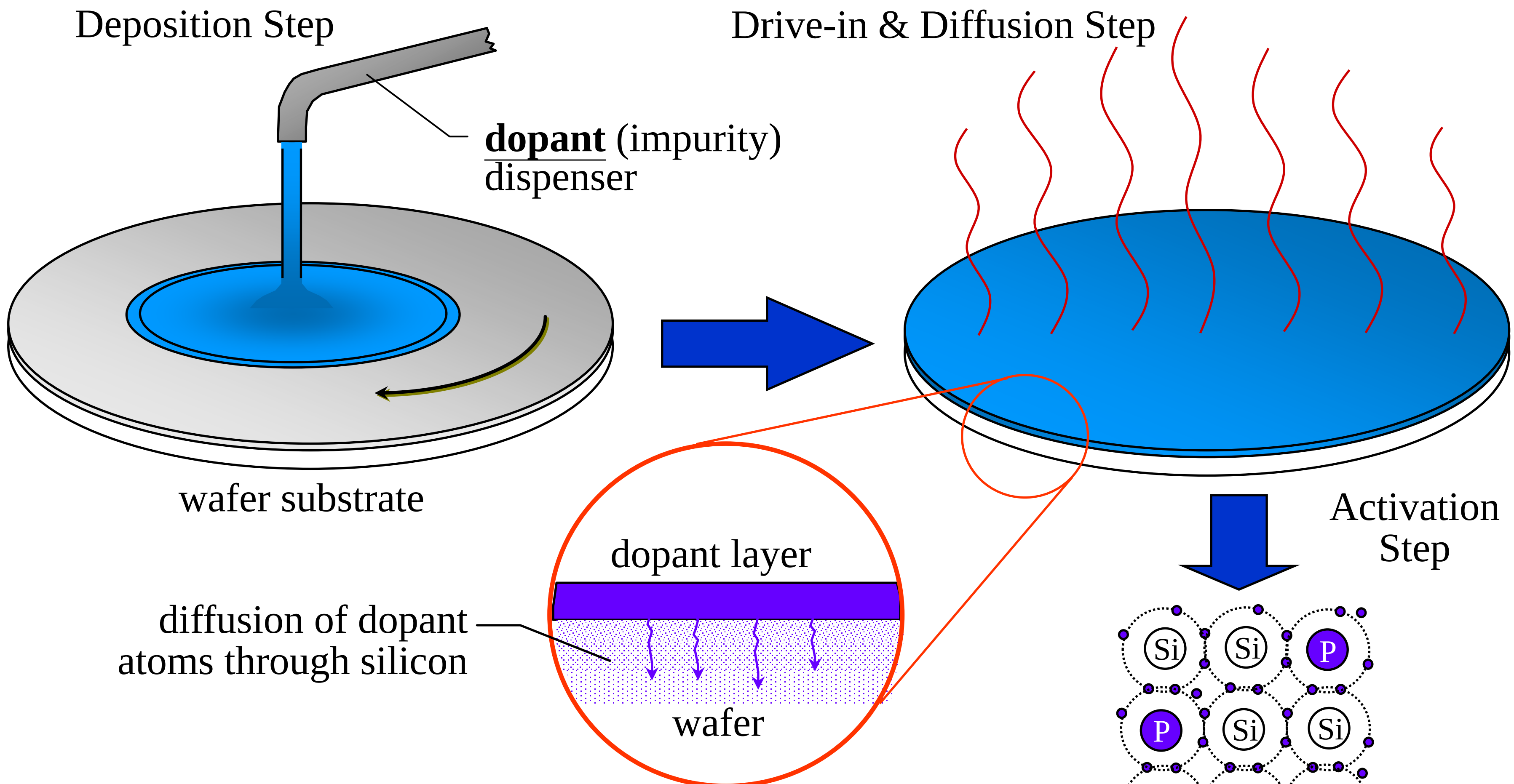


Silicon wafer

Why Silicon:
1. Abundance of silicon (25%, the second)
2. Higher melting temperature for wider processing range (1412°C)
3. Wider temperature range of operation (Eg> Ge)
4. Natural growth of silicon dioxide (MOS)

Figure 2.20

Doping of Silicon (intrinsic→ extrinsic)



Pure silicon : ρ= 2.5x10^5 ohm-cm

If doped one in every 10^6 silicon atom, then ρ= 0.2 ohm-cm

Figure 2.21

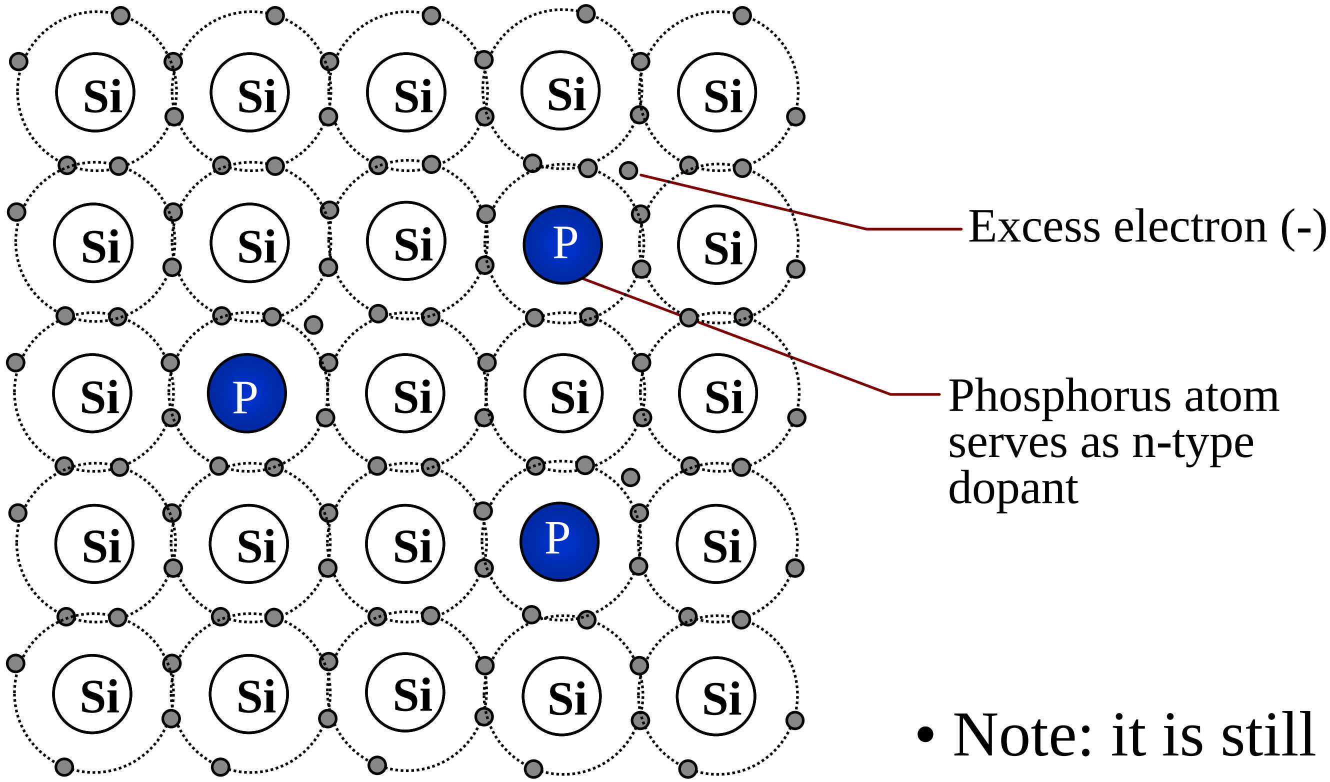
Silicon Dopants

Acceptor Impurities	Semiconductor	Donor Impurities
Group III (p-type)	**Group IV**	**Group V (n-type)**
Boron 5	Carbon 6	Nitrogen 7
Aluminum 13	**Silicon 14**	**Phosphorus 15**
Gallium 31	Germanium 32	**Arsenic 33**
Indium 49	Tin 50	**Antimony 51**

** Items underlined are the most commonly used in silicon-based IC manufacturing.*

Figure 2.22

Electrons in N-Type Silicon with Phosphorus Dopant



Donor atoms provide excess electrons to form n-type silicon.

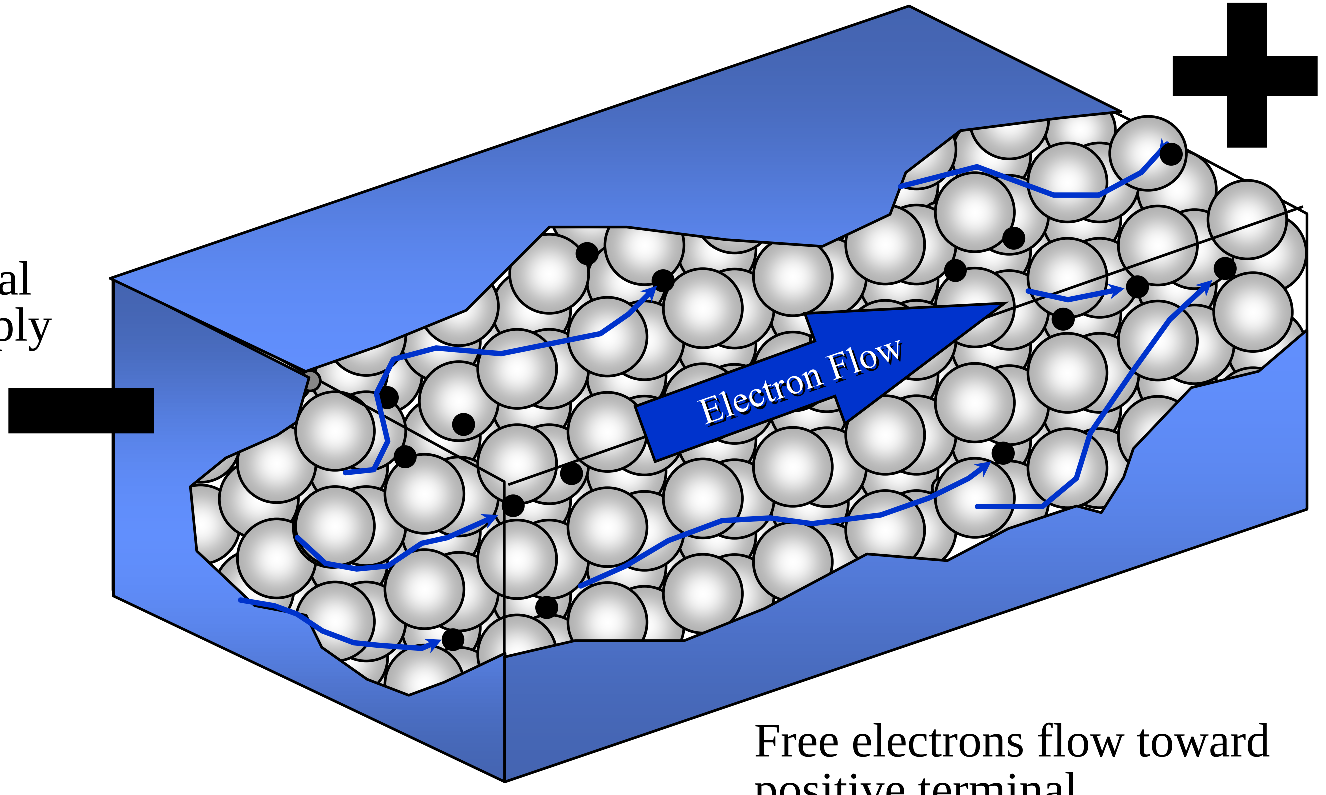
- Note: it is still **neutral**
- **Majority is electron**

Figure 2.23

Conduction in n-Type Silicon

Positive terminal from power supply

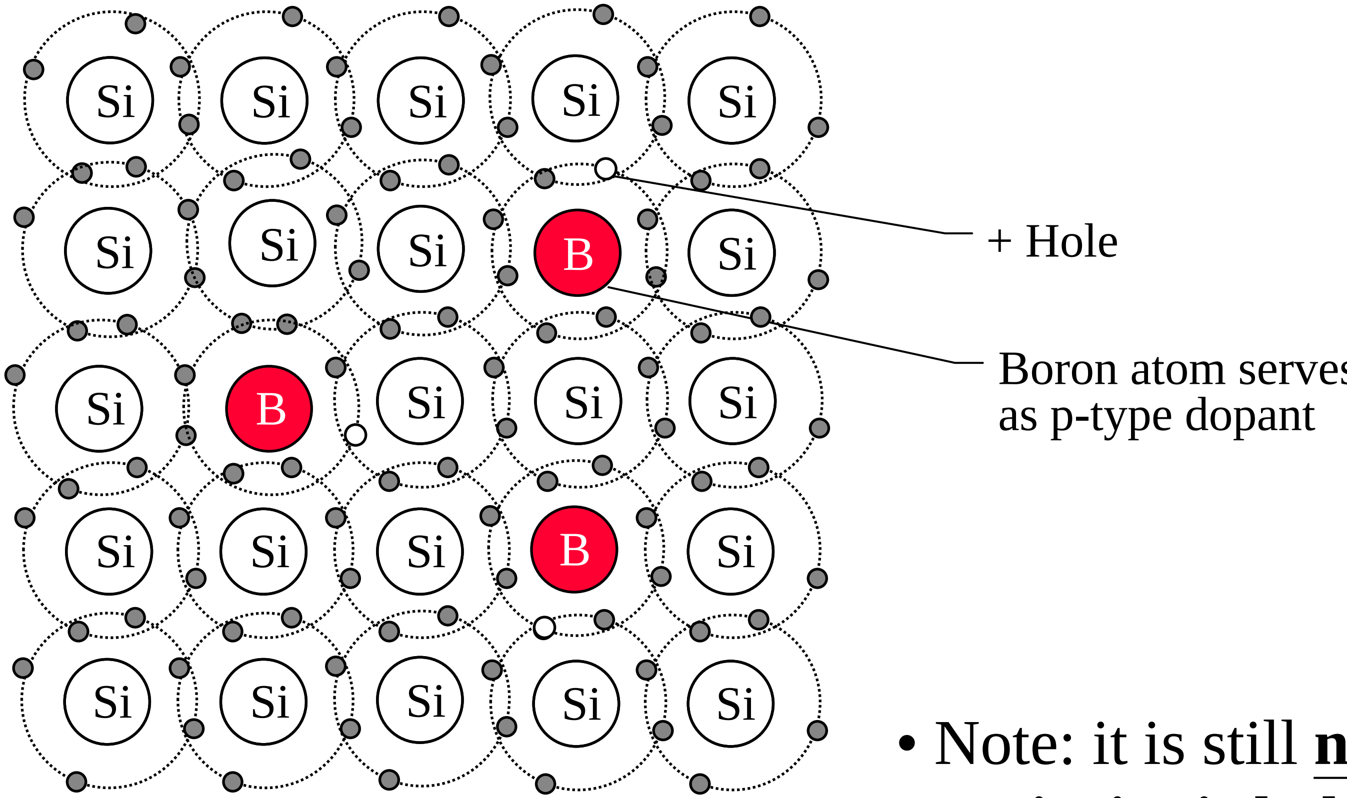
Negative terminal from power supply



Free electrons flow toward positive terminal.

Figure 2.24

Holes in p-Type Silicon with Boron Dopant



Acceptor atoms provide a deficiency of electrons to form p-type silicon.

- Note: it is still **neutral**
- **Majority is hole**
- **Minority is electron**

Figure 2.25

Conduction in p-Type Silicon

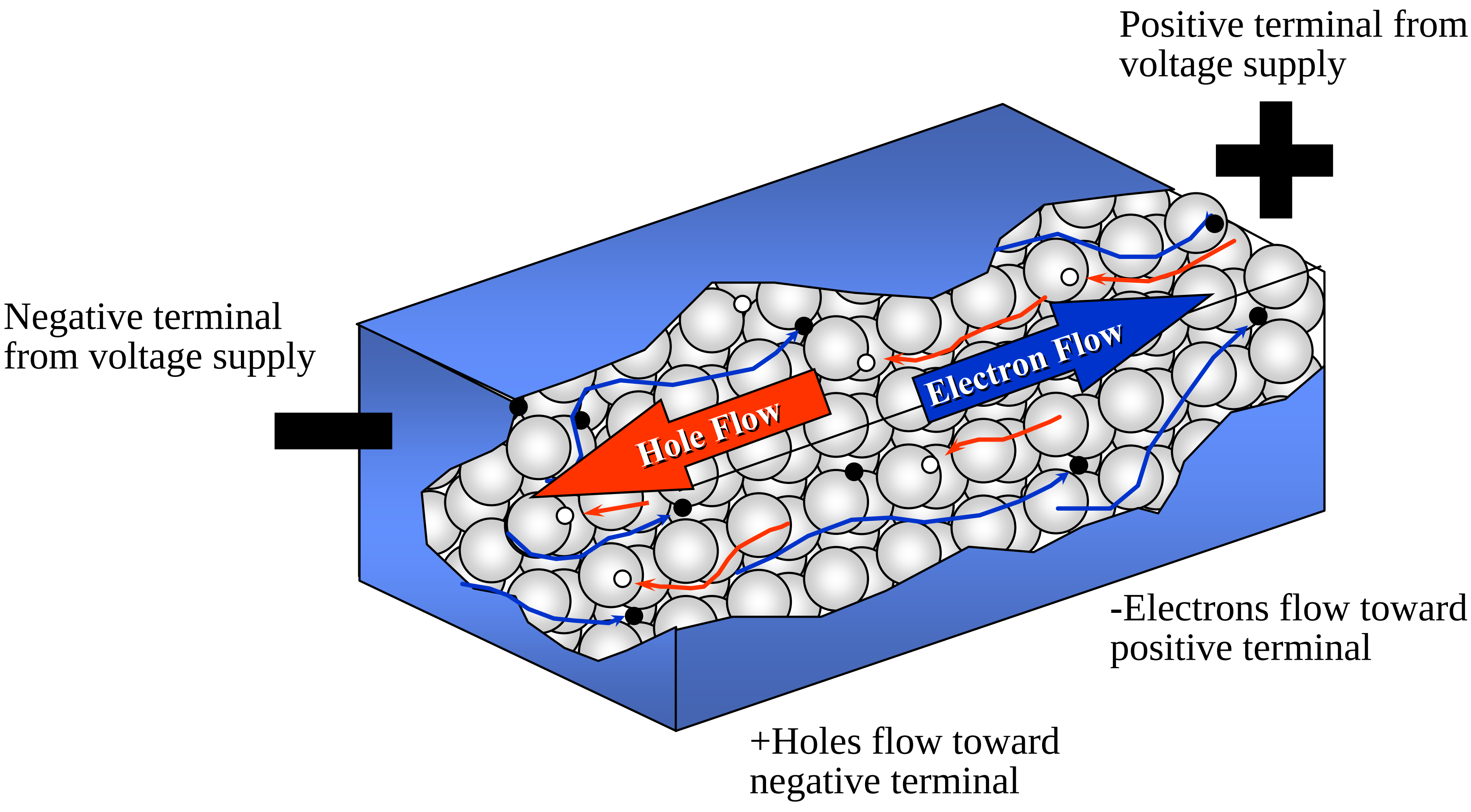
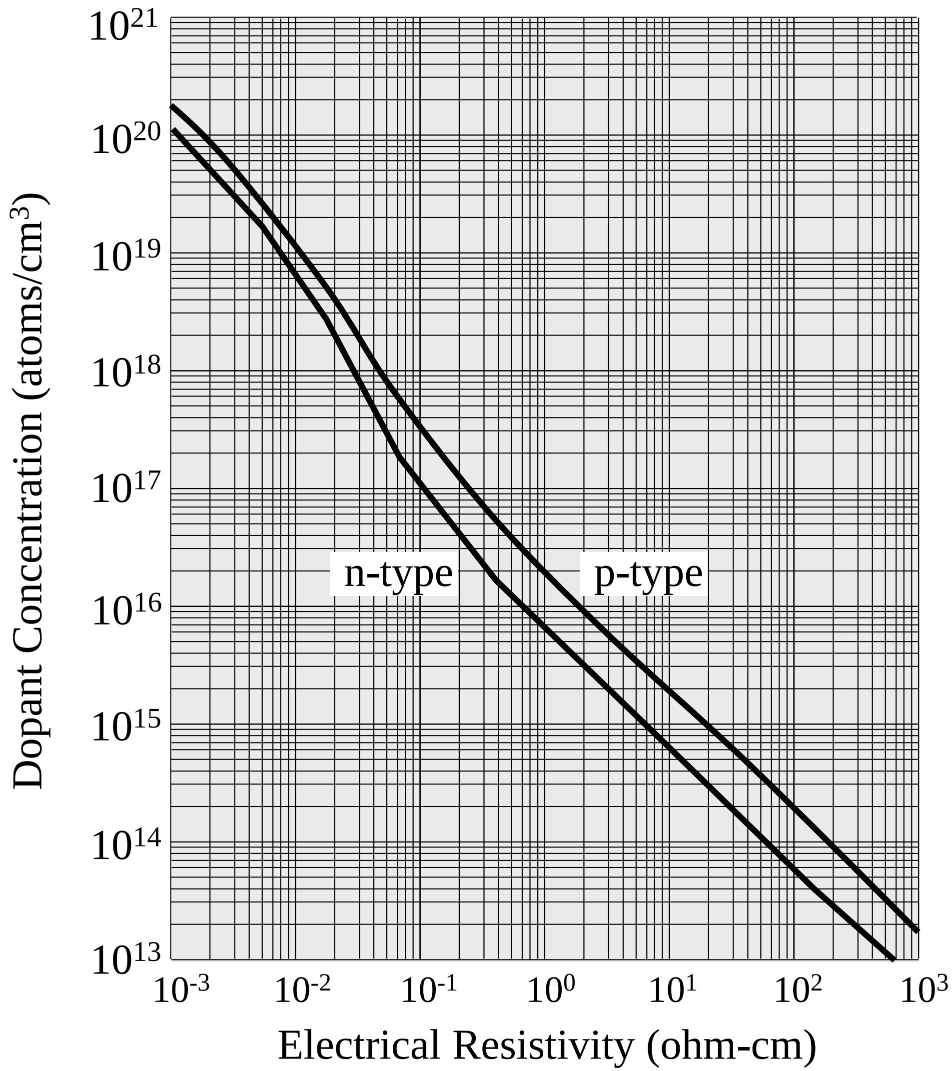


Figure 2.26

Silicon Resistivity Versus Dopant Concentration



Redrawn from *VLSI Fabrication Principles, Silicon and Gallium Arsenide*, John Wiley & Sons, Inc.

Figure 2.27

Cross Section of Planar pn Junction

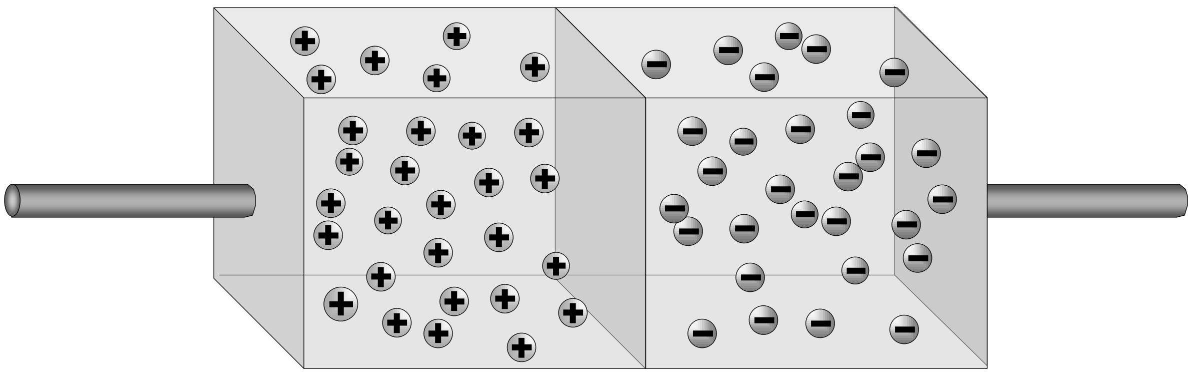


Figure 2.28

Alternative Semiconductor Materials

Comparison of Some Physical Properties for Semiconductor Materials				
Property	**Si**	**Ge**	**GaAs**	**SiO_2**
Melting point (°C)	1412	937	1238	1700 (approx.)
Atomic Weight	28.09	72.60	144.63	60.08
Atomic Density (atoms/cm^3)	4.99×10^{22}	4.42×10^{22}	2.21×10^{22}	2.3×10^{22}
Energy Band Gap (eV)	1.11	0.67	1.40	8 (approx.)

Table 2.3

Gallium Arsenide (GaAs)

- GaAs is the most common III-V compound semiconductor
- GaAs has greater electron mobility
- Applications: react to high-frequency microwave signal for communication system.
- GaAs substrate (high E_g) has an increased resistivity ($10^8\ \Omega$-cm) and higher radiation hardness, attractive for military and space applications
- Disadvantage: lack of a natural oxide, fragility, toxicity of As and cost is high