

Semiconductors: A general introduction

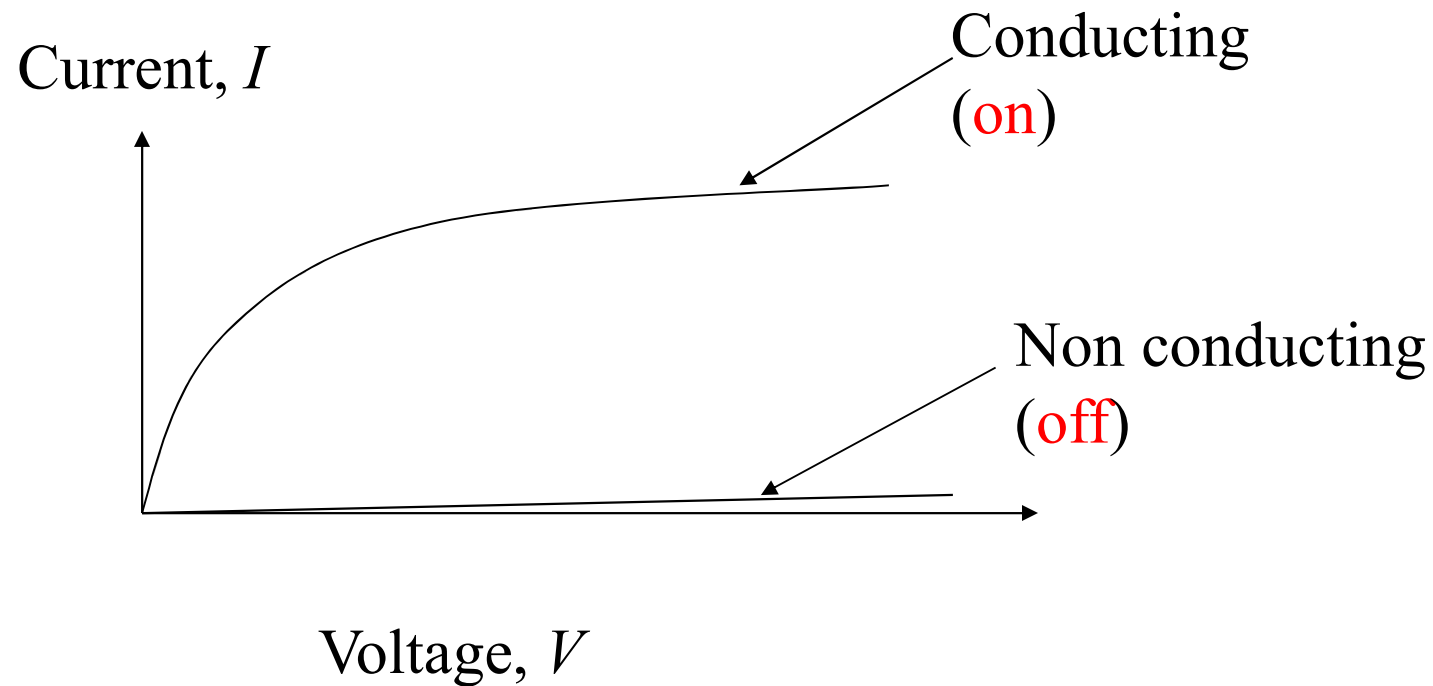
Classification of Materials in terms of electrical resistivity:

Insulators	$10^{10} - 10^{18} \ \Omega \text{ cm}$
Semiconductors	$10^{-4} - 10^8 \ \Omega \text{ cm}$
Conductors	$10^{-6} - 10^{-4} \ \Omega \text{ cm}$

The uniqueness of semiconductors is that their conductivity can be varied **by us** over a wide range, e.g. by

- adding minute quantities of impurities
- by applying electric field
- illumination

Introduction



We can use this **as a switch**. (Example: Digital computers)

Periodic table of the elements

Periodic System of Elements																		VIII		
Dimitri Mendeleev (1869)																				
IA		IIA												IIIA	IVA	VA	VIA	VIIA		
1 1.01 H Hydrogen 1s ¹		3 6.94 Li Lithium 2s ¹	4 9.01 Be Beryllium 2s ²											5 10.8 B Boron 2p ¹	6 12.0 C Carbon 2p ²	7 14.0 N Nitrogen 2p ³	8 16.0 O Oxygen 2p ⁴	9 19.0 F Fluorine 2p ⁵	10 20.2 Ne Neon 2p ⁶	
11 23.0 Na Sodium 3s ¹	12 24.3 Mg Magnesium 3s ²			IIIB	IVB	VB	VIB	VIIB	VIII		IB	IIB	13 27.0 Al Aluminum 3p ¹	14 28.1 Si Silicon 3p ²	15 31.0 P Phosphorous 3p ³	16 32.1 S Sulfur 3p ⁴	17 35.5 Cl Chlorine 3p ⁵	18 40.0 Ar Argon 3p ⁶		
19 39.1 K Potassium 4s ¹	20 40.1 Ca Calcium 4s ²	21 45.0 Sc Scandium 3d ¹ 4s ²	22 47.9 Ti Titanium 3d ² 4s ²	23 50.9 V Vanadium 3d ³ 4s ²	24 52.0 Cr Chromium 3d ⁵ 4s ¹	25 54.9 Mn Manganese 3d ⁵ 4s ²	26 55.9 Fe Iron 3d ⁶ 4s ²	27 58.9 Co Cobalt 3d ⁷ 4s ²	28 58.7 Ni Nickel 3d ⁸ 4s ²	29 63.5 Cu Copper 3d ¹⁰ 4s ¹	30 65.4 Zn Zinc 3d ¹⁰ 4s ²	31 69.7 Ga Gallium 4p ¹	32 72.6 Ge Germanium 4p ²	33 74.9 As Arsenic 4p ³	34 79.0 Se Selenium 4p ⁴	35 79.9 Br Bromine 4p ⁵	36 83.8 Kr Krypton 4p ⁶			
37 85.5 Rb Rubidium 5s ¹	38 87.6 Sr Strontium 5s ²	39 88.9 Y Yttrium 4d ¹ 5s ²	40 91.2 Zr Zirconium 4d ² 5s ²	41 92.9 Nb Niobium 4d ⁴ 5s ¹	42 95.9 Mo Molybdenum 4d ⁵ 5s ¹	43 98 Tc Technetium 4d ⁵ 5s ²	44 101 Ru Ruthenium 4d ⁷ 5s ¹	45 103 Rh Rhodium 4d ⁸ 5s ¹	46 106 Pd Palladium 4d ¹⁰	47 108 Ag Silver 4d ¹⁰ 5s ¹	48 112 Cd Cadmium 4d ¹⁰ 5s ²	49 115 In Indium 5p ¹	50 119 Sn Tin 5p ²	51 122 Sb Antimony 5p ³	52 128 Te Tellurium 5p ⁴	53 127 I Iodine 5p ⁵	54 131 Xe Xenon 5p ⁶			
55 133 Cs Cesium 6s ¹	56 137 Ba Barium 6s ²	57 139 La* Lanthanum 5d ¹ 6s ²	72 178 Hf Hafnium 5d ² 6s ²	73 181 Ta Tantalum 5d ³ 6s ²	74 184 W Tungsten 5d ⁴ 6s ²	75 186 Re Rhenium 5d ⁵ 6s ²	76 190 Os Osmium 5d ⁶ 6s ²	77 192 Ir Iridium 5d ⁷ 6s ²	78 195 Pt Platinum 5d ⁹ 6s ¹	79 197 Au Gold 5d ¹⁰ 6s ¹	80 201 Hg Mercury 5d ¹⁰ 6s ²	81 204 Tl Thallium 6p ¹	82 207 Pb Lead 6p ²	83 209 Bi Bismuth 6p ³	84 209 Po Polonium 6p ⁴	85 210 At Astatine 6p ⁵	86 222 Rn Radon 6p ⁶			
87 223 Fr Francium 7s ¹	88 226 Ra Radium 7s ²	89 227 Ac** Actinium 6d ¹ 7s ²																		
Alkaline metals		Alkaline-earth metals												Coinage metals		Elemental semiconductors		Halogens		Noble gases
														</						

Abbreviated periodic table of the elements

4 Be	5 B	6 C	7 N	8 O
12 Mg	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Elements

$$E_{\text{Si}} = 1.1 \text{ eV}$$

$$E_{\text{Ge}} = 0.67 \text{ eV}$$

Compounds

$$E_{\text{GaAs}} = 1.43 \text{ eV}$$

$$E_{\text{GaSb}} = 0.7 \text{ eV}$$

$$E_{\text{GaN}} = 3.4 \text{ eV}$$

The most common semiconductor is **Silicon**

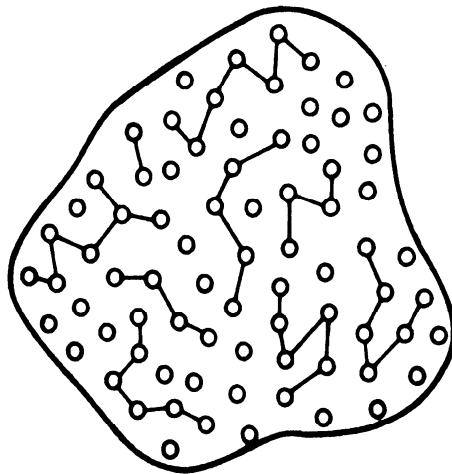
Semiconductor materials

Table 1.1 Semiconductor Materials.

<i>General Classification</i>	<i>Symbol</i>	<i>Semiconductor Name</i>
(1) Elemental	Si Ge	Silicon Germanium
(2) Compounds		
(a) IV-IV	SiC	Silicon carbide
(b) III-V	AlP	Aluminum phosphide
	AlAs	Aluminum arsenide
	AlSb	Aluminum antimonide
	GaN	Gallium nitride
	GaP	Gallium phosphide
	GaAs	Gallium arsenide
	GaSb	Gallium antimonide
	InP	Indium phosphide
	InAs	Indium arsenide
	InSb	Indium antimonide
(c) II-VI	ZnO	Zinc oxide
	ZnS	Zinc sulfide
	ZnSe	Zinc selenide
	ZnTe	Zinc telluride
	CdS	Cadmium sulfide
	CdSe	Cadmium selenide
	CdTe	Cadmium telluride
	HgS	Mercury sulfide
(d) IV-VI	PbS	Lead sulfide
	PbSe	Lead selenide
	PbTe	Lead telluride
(3) Alloys		
(a) Binary	$\text{Si}_{1-x}\text{Ge}_x$	
(b) Ternary	$\text{Al}_x\text{Ga}_{1-x}\text{As}$	(or $\text{Ga}_{1-x}\text{Al}_x\text{As}$)
	$\text{Al}_x\text{In}_{1-x}\text{As}$	(or $\text{In}_{1-x}\text{Al}_x\text{As}$)
	$\text{Cd}_{1-x}\text{Mn}_x\text{Te}$	
	$\text{GaAs}_{1-x}\text{P}_x$	
	$\text{Ga}_x\text{In}_{1-x}\text{As}$	(or $\text{In}_{1-x}\text{Ga}_x\text{As}$)
	$\text{Ga}_x\text{In}_{1-x}\text{P}$	(or $\text{In}_{1-x}\text{Ga}_x\text{P}$)
	$\text{Hg}_{1-x}\text{Cd}_x\text{Te}$	
(c) Quaternary	$\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$	
	$\text{Ga}_x\text{In}_{1-x}\text{As}_{1-y}\text{P}_y$	

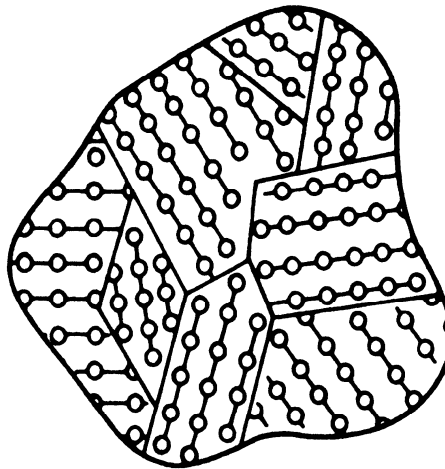
Crystalline solids

The fact that one can alter the properties of semiconductors over a wide range may have something to do with the atomic arrangement of atoms in these materials. So, let us look at the crystal structure.



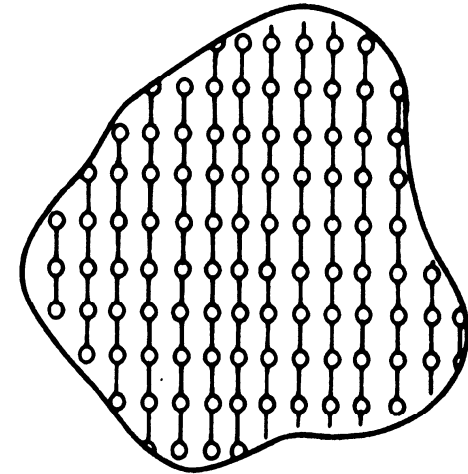
(a) Amorphous

No recognizable
long-range order



(b) Polycrystalline

Completely ordered
in segments



(c) Crystalline

Entire solid is made up of
atoms in an orderly array

Figure 1.1

Crystalline solids

Lattice: Periodic arrangement of atoms. The atomic arrangement determines the macro-properties of the crystal.

Examples:

- Amorphous Si thin film transistors used as switching devices in LCDs
- Polycrystalline Si used as gate in MOSFETs
- Actual active region of MOSFET is fabricated in crystalline Si

Unit cell concept

The *unit cell* is a small portion of any given crystal that could be used to reproduce a crystal.

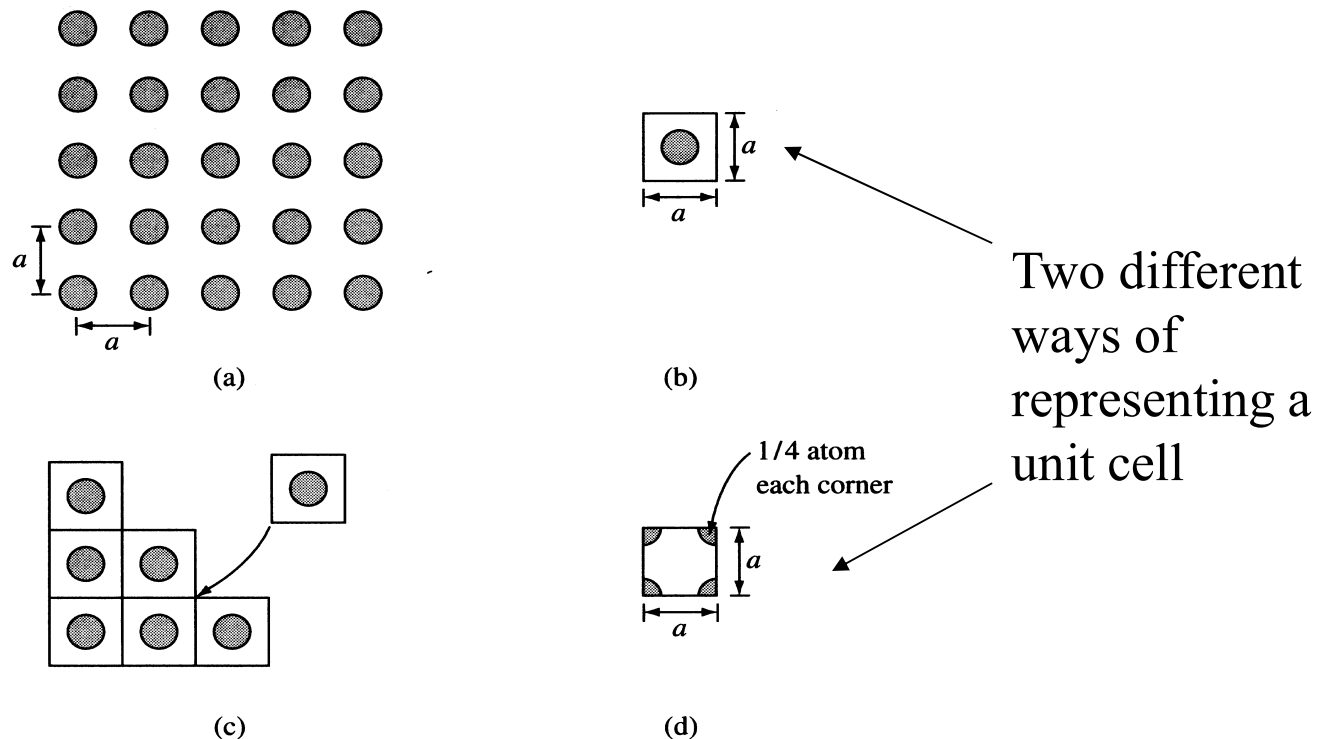
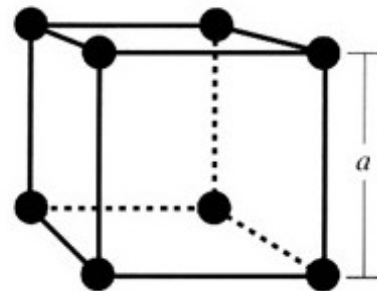
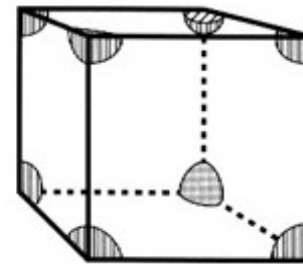


Figure 1.2

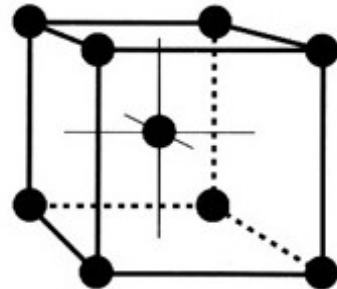
Simple 3D unit cells



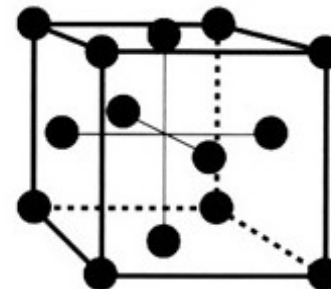
(a) Simple cubic



(b) Pedantically correct
simple cubic



(c) bcc



(d) fcc

Figure 1.3 Simple three-dimensional unit cells. (a) Simple cubic unit cell. (b) Pedantically correct simple cubic unit cell including only the fractional portion ($1/8$) of each corner atom actually within the cell cube. (c) Body centered cubic unit cell. (d) Face centered cubic unit cell.

Crystal structure of Si and Ge and other common semiconductors

- 2 FCC lattices displaced by $((\frac{1}{4}) a, (\frac{1}{4}) a, (\frac{1}{4}) a)$ along body diagonal*
- 8 atoms per unit cell
- Diamond lattice (also called “zincblende” if interpenetrating FCC lattices are made of different elements like in GaAs)
- Each atom is bonded to 4 other atoms (tetrahedral bonding structure)

* The lattice constant or cubic edge is “ a ”. Generally a is expressed in Angstroms. $1 \text{ \AA} = 10^{-8} \text{ cm} = 10^{-10} \text{ m}$

Diamond and zincblende lattice unit cells

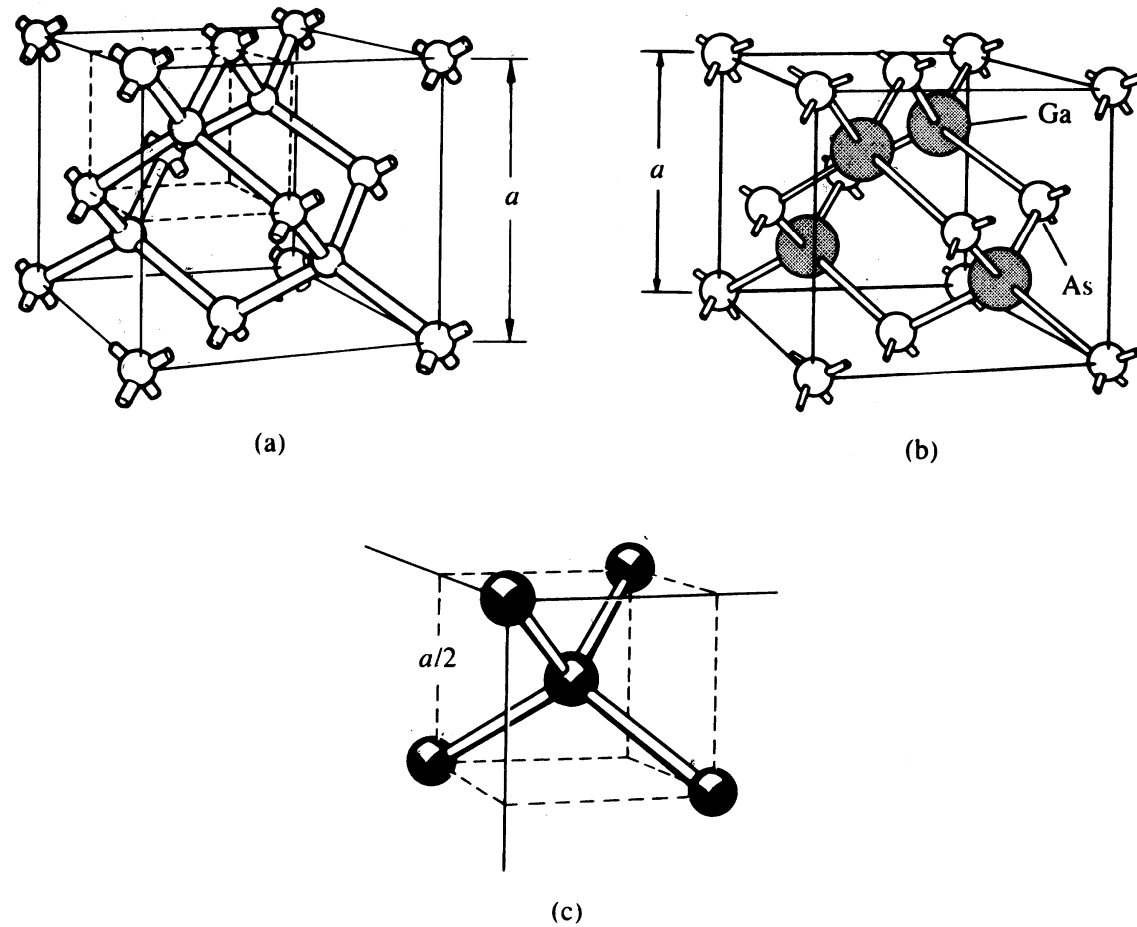
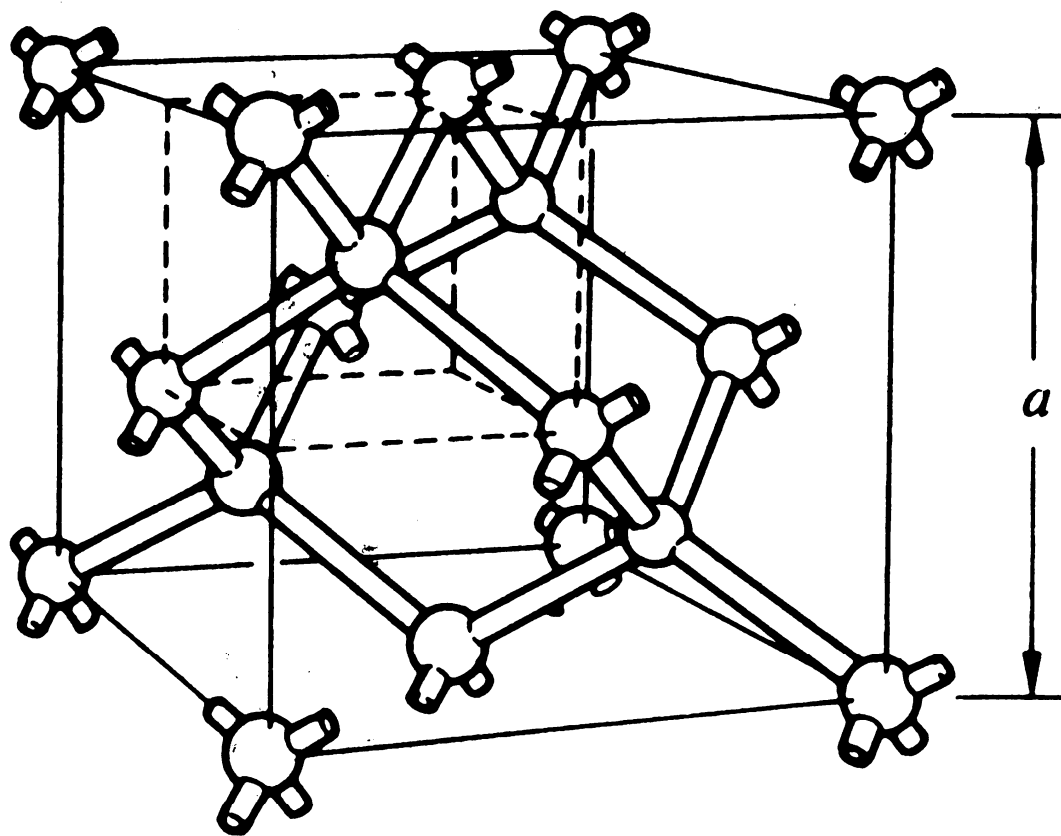


Figure 1.4

Diamond lattice (detail)



(a)

Example

What is the number of Si atoms in 1 cm³ of Si?

Given is the lattice constant: $a = 5.43 \text{ \AA}$

$$\frac{8 \text{ atoms}}{a^3} = 5 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3}$$

What is the density of Si?

Atomic weight of Si = 28.1 i.e. 1 mole ($N_A = 6.023 \times 10^{23}$ atoms) of Si has a mass of 28.1 g

$$\text{Density} = \frac{5 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3} \times 28.1 \frac{\text{gm}}{\text{mole}}}{6.02 \times 10^{23} \frac{\text{atoms}}{\text{mole}}} = 2.33 \frac{\text{g}}{\text{cm}^3}$$