Semiconductor Devices

Chapter 1
The Crystal Structure of Solids

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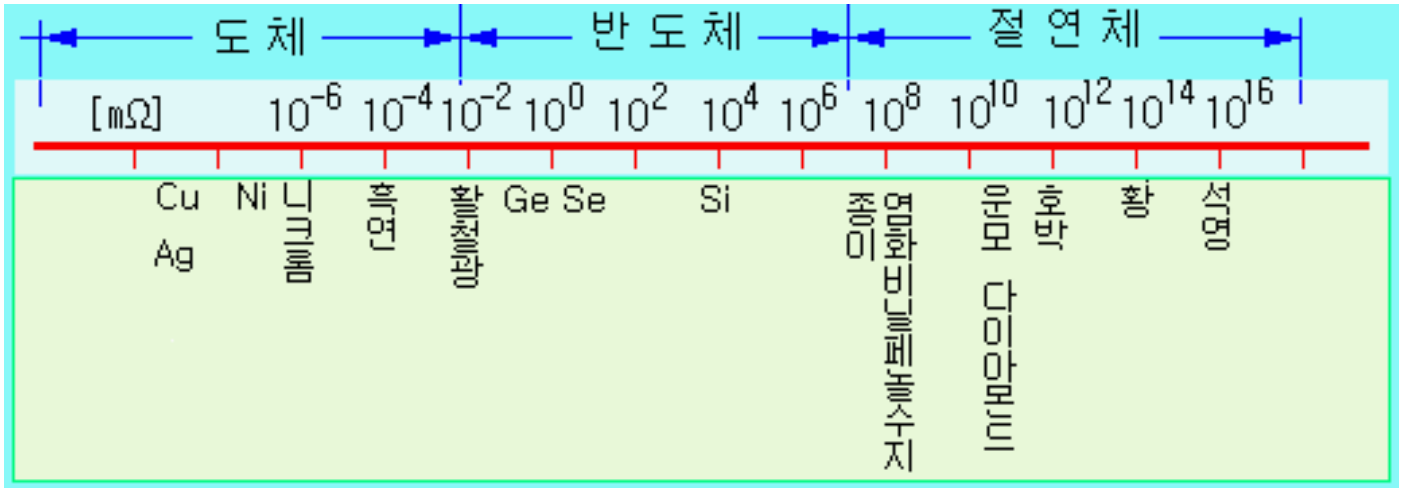
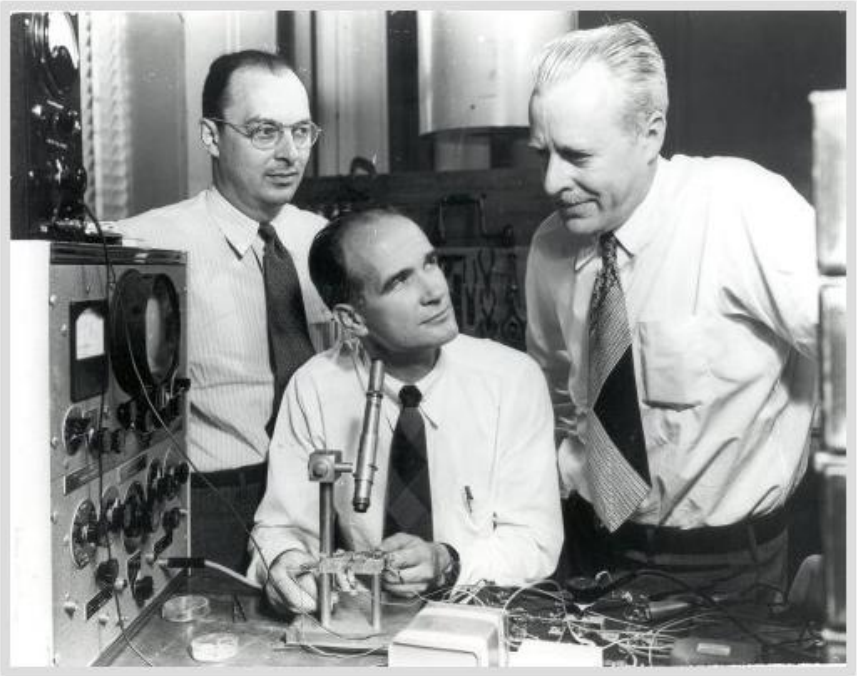
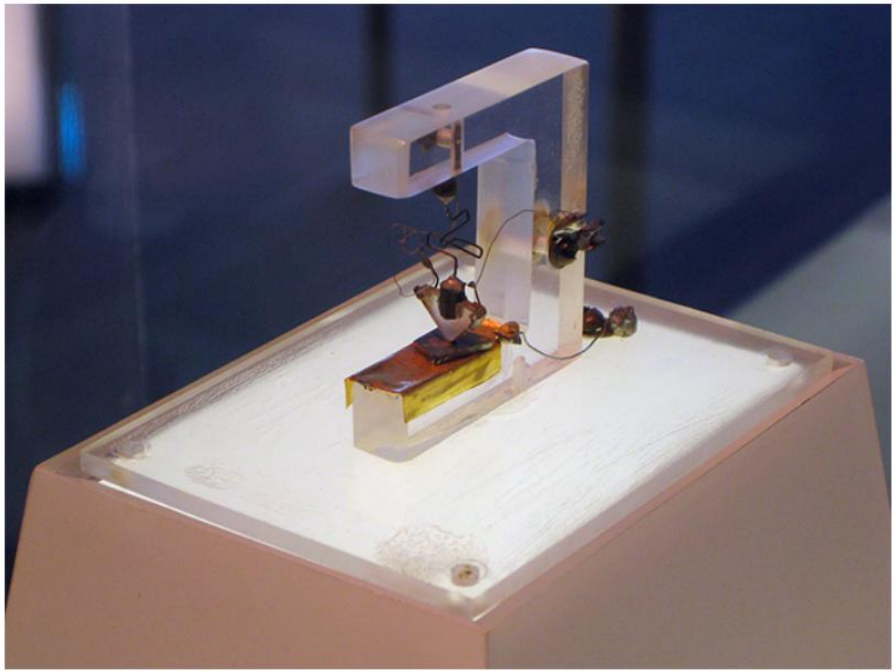

도 체
반 도 체
절 연 체
[mΩ]
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16}
Cu
Ag
Ni
니크롬
흑연
활철광
Ge
Se
Si
종이
염화비닐
폴리에스테르수지
운모
다이아몬드
호박
황
석영



John Bardeen, William Shockley and Walter Brattain, the inventors of the first point-contact transistor in December of 1947. The three would share the 1956 Nobel Prize in physics for their work.



First transistor

Table 1.1 | A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorus
31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

Table 1.2 | A list of some semiconductor materials

Elemental semiconductors	
Si	Silicon
Ge	Germanium
Compound semiconductors	
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
GaP	Gallium phosphide
GaAs	Gallium arsenide
InP	Indium phosphide

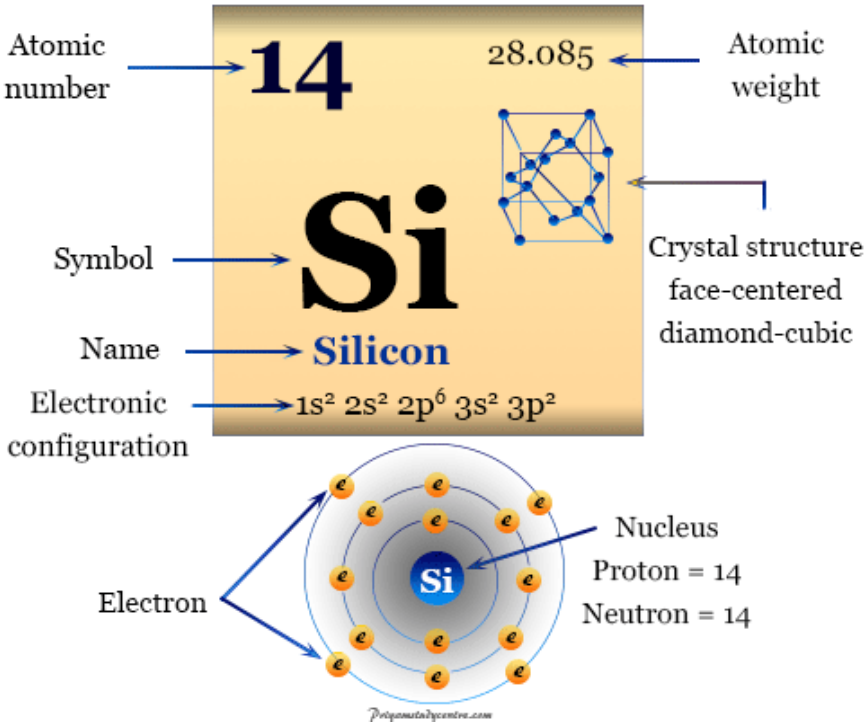
The Periodic Table of the Elements

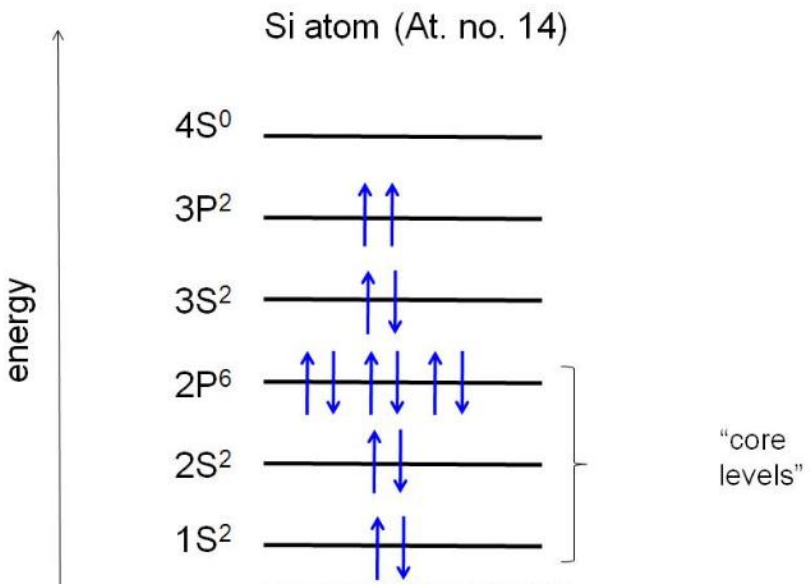
IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 1.008 H Hydrogen																	2 4.0026 He Helium
3 6.939 Li Lithium	4 9.012 Be Beryllium	Transition Metals										5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Florine	10 20.183 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 1137.34 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)

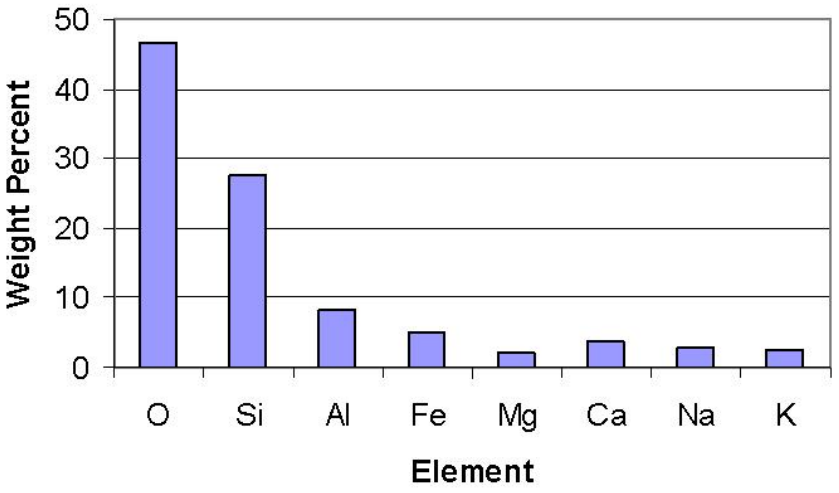
Lanthanides	58 140.12 Ce Cerium	59 140.91 Pr Praseodym-ium	60 144.24 Nd Neodym-ium	61 147 Pm Prome-thium	62 150.35 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolin-ium	65 158.92 Tb Terbium	66 162.50 Dy Dyspro-sium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	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


Atomic number
14
28.085
Atomic weight
Si
Symbol
Name
Silicon
Electronic configuration
1s² 2s² 2p⁶ 3s² 3p²
Crystal structure face-centered diamond-cubic
Si
Electron
Nucleus
Proton = 14
Neutron = 14


Si atom (At. no. 14)
energy
4S⁰
3P²
3S²
2P⁶
2S²
1S²
"core levels"

Why Silicon?

- Abundance of silicon
- Higher melting temp. for wider processing range
- Wider temp. range of operation
- Natural growth of silicon dioxide



The 8 most common elements in Earth's crust:
46.6% Oxygen (O)
27.7% Silicon (Si)
8.1% Aluminum (Al)
5.0% Iron (Fe)
3.6% Calcium (Ca)
2.8% Sodium (Na)
2.6% Potassium (K)
2.1% Magnesium (Mg)

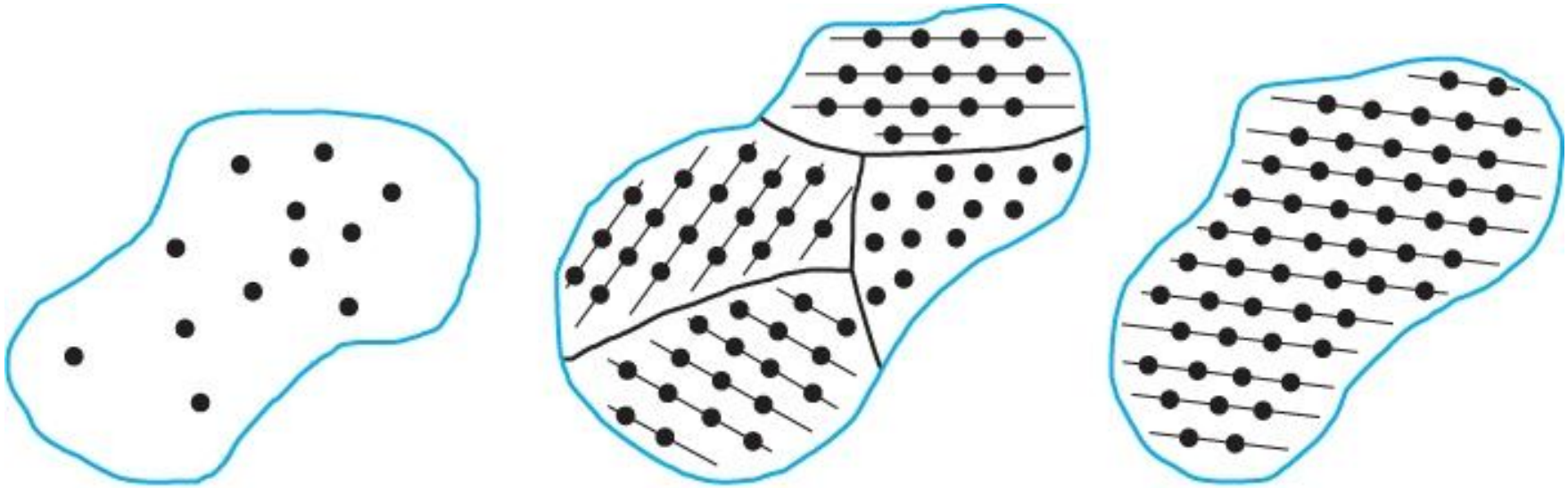


Figure 1.1 | Schematics of three general types of crystals: (a) amorphous, (b) polycrystalline, (c) single.

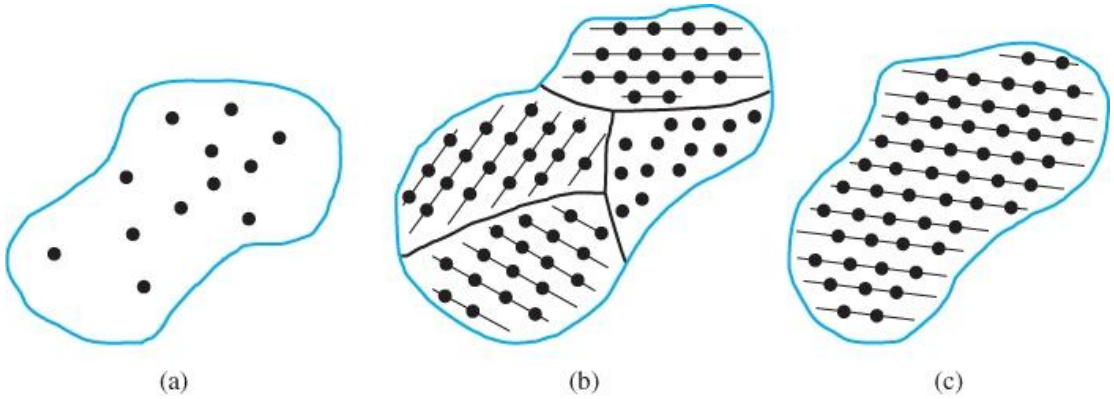
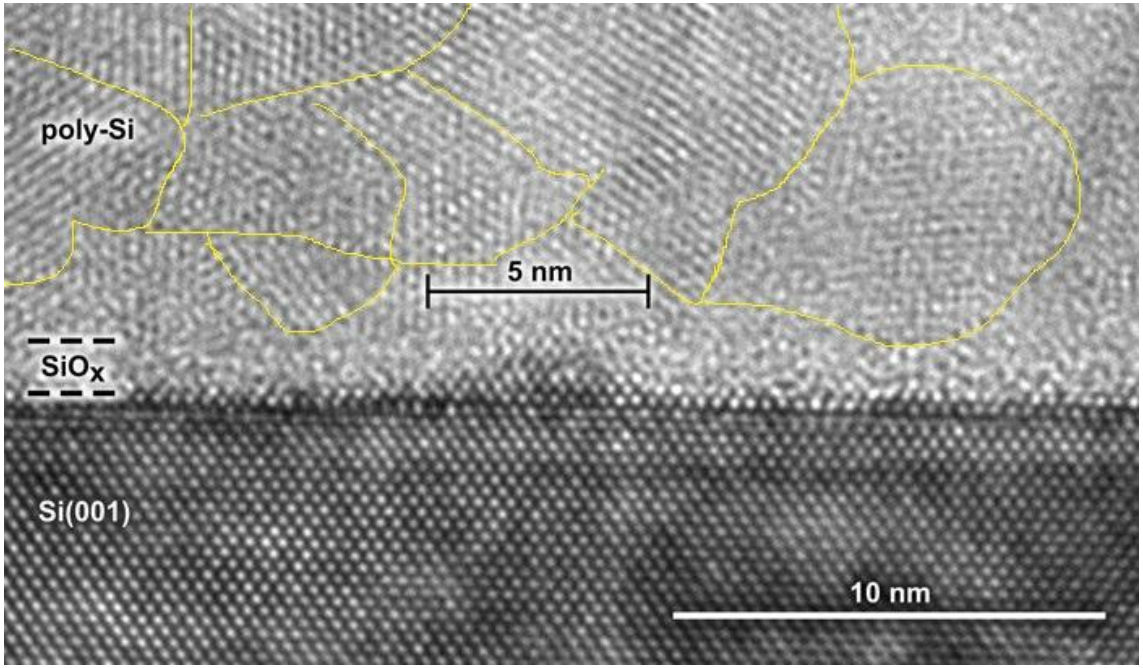
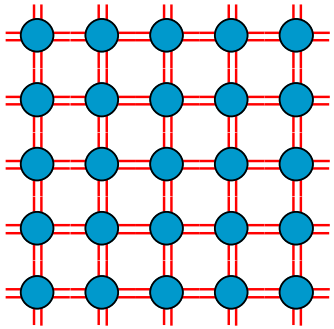
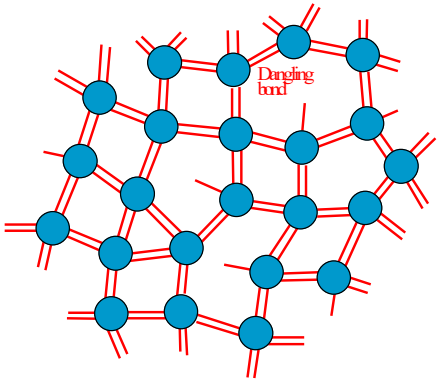


Figure 1.1 | Schematics of three general types of crystals: (a) amorphous, (b) polycrystalline, (c) single.

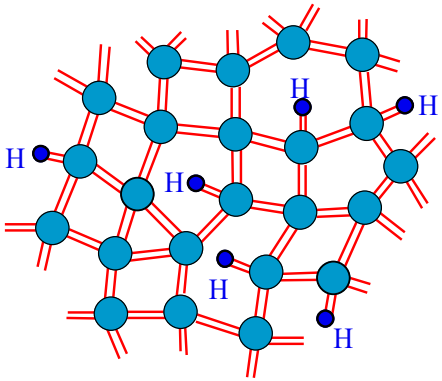




(a) Two dimensional schematic representation of a silicon crystal



(b) Two dimensional schematic representation of the structure of amorphous silicon. The structure has voids and dangling bonds and there is no long range order.



(c) Two dimensional schematic representation of the structure of hydrogenated amorphous silicon. The number of hydrogen atoms shown is exaggerated.

Fig. 1.58: Silicon can be grown as a semiconductor crystal or as an amorphous semiconductor film. Each line represents an electron in a bond. A full covalent bond has two lines and a broken bond has one line.

From *Principles of Electronic Materials and Devices, Second Edition*, S.O. Kasap (© McGraw-Hill, 2002)
http://Materials.Usask.Ca

	Crystalline Si c-Si	Amorphous Si a-Si	Hydrogenated a-Si a-Si:H
Structure	Diamond cubic.	Short range order only. On average, each Si covalently bonds with four Si atoms. Has microvoids and dangling bonds	Short range order only. Structure contains typically 10% H. Hydrogen atoms passivate dangling bonds and relieve strain from bonds.
Typical Preparation	Czochralski technique	Electron beam evaporation of Si	Chemical vapor deposition (CVD) of silane gas by RF (radio frequency) plasma.
Density g cm^{-3}	2.33	About 3-10% less dense.	About 1-3% less dense
Electronic Applications	Discrete and integrated electronic devices.	None	Large area electronic devices such as solar cells, thin film transistor arrays in flat panel displays and photoconductor drums used in photocopying.

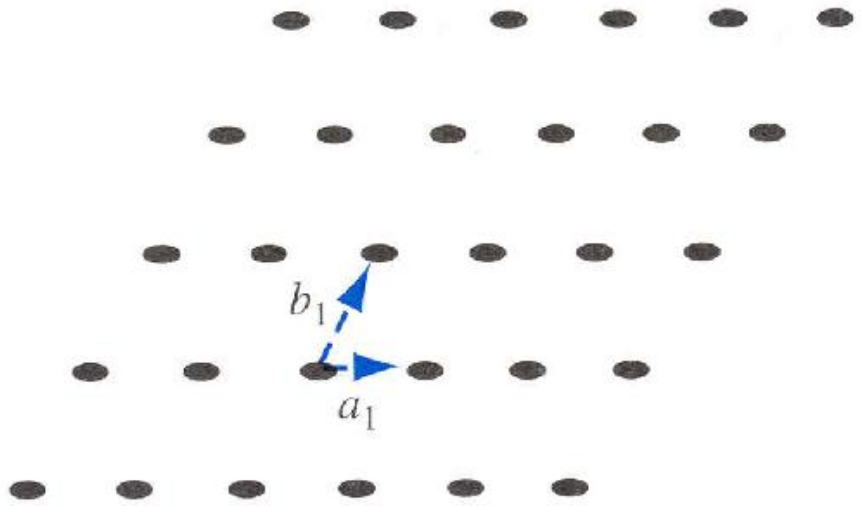


Figure 1.2 | Two-dimensional representation of a single-crystal lattice.

-lattice

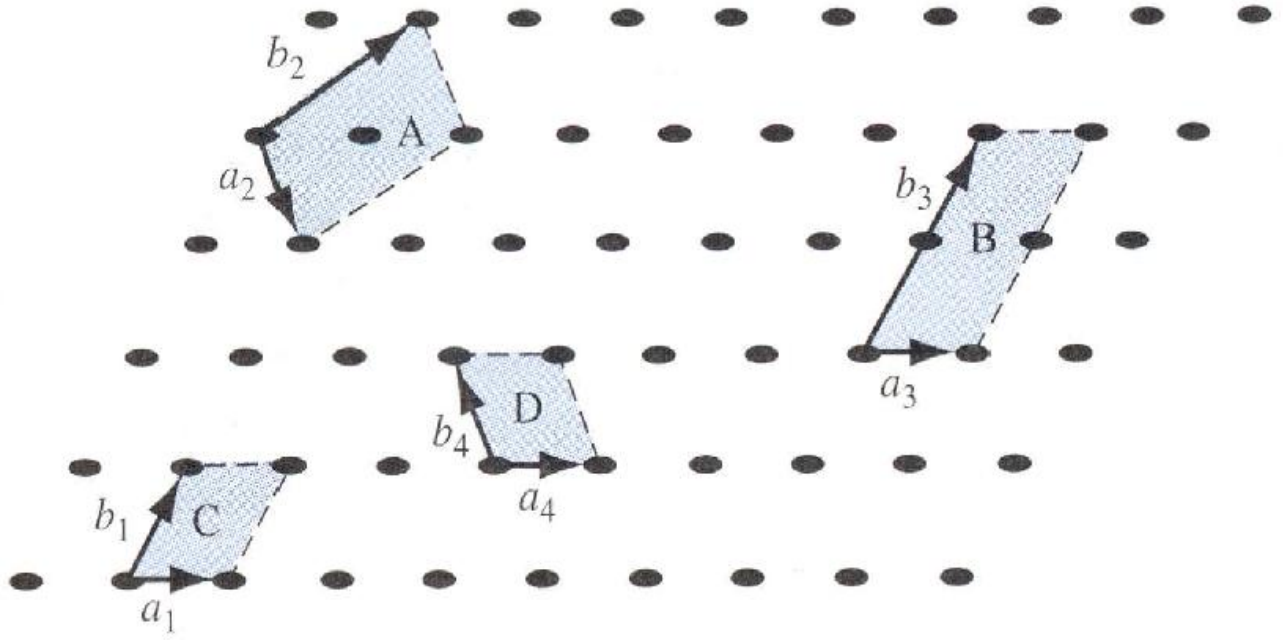


Figure 1.3 | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

- unit cell

- effective # of atoms

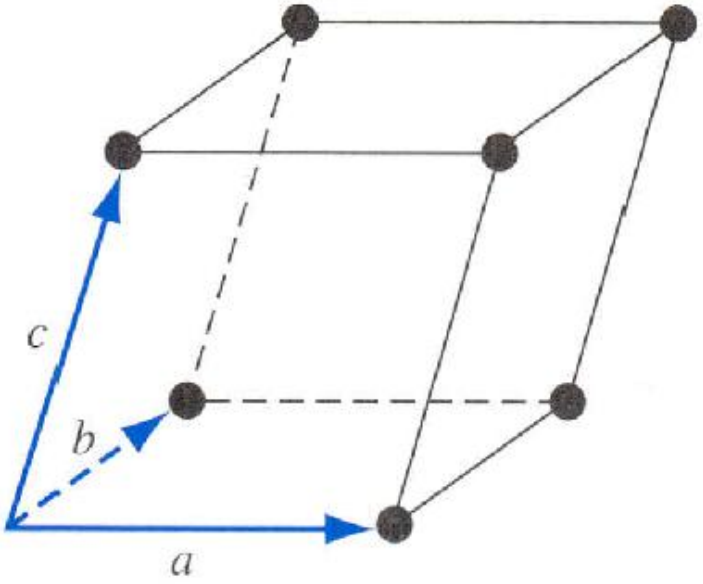
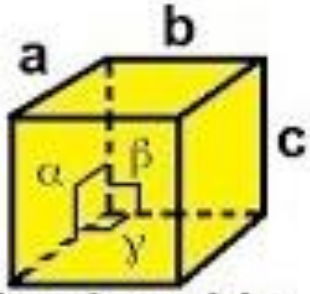


Figure 1.4 | A generalized primitive unit cell.

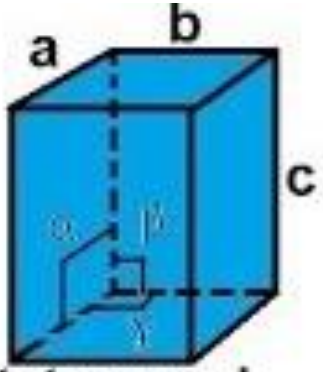
- primitive cell → (effective # of atoms = 1)

$$\bar{r} = p\bar{a} + q\bar{b} + s\bar{c} \qquad (1\text{-}1)$$

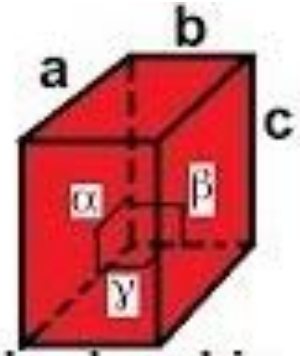
Crystal Systems (7 crystal system)



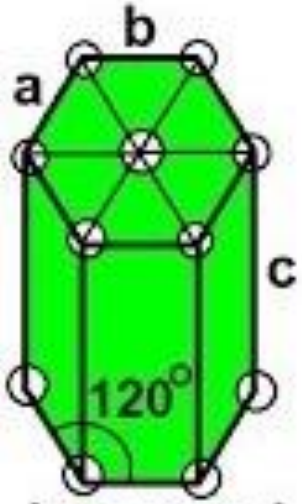
simple cubic
a = b = c
$\alpha = \beta = \gamma = 90^o$



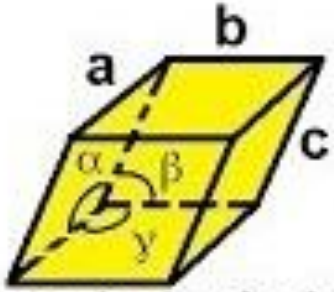
tetragonal
a = b ≠ c
$\alpha = \beta = \gamma = 90^o$



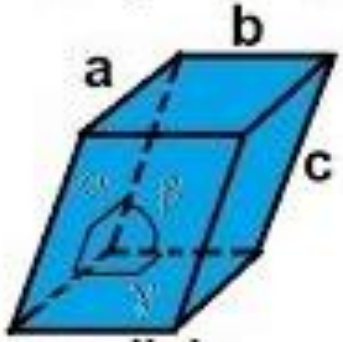
orthorhombic
a ≠ b ≠ c
$\alpha = \beta = \gamma = 90^o$



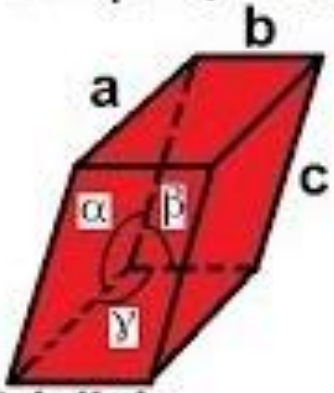
hexagonal
a = b ≠ c
$\alpha = \beta = 90^o$
$\gamma = 120^o$



rhombohedral
a = b = c
$\alpha = \beta = \gamma \neq 90^o$

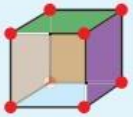
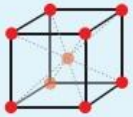
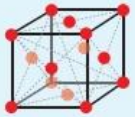
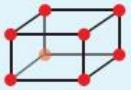
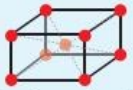
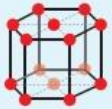
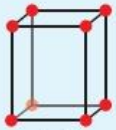
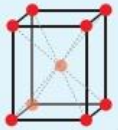
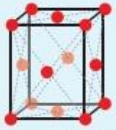
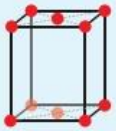
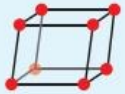
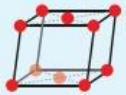
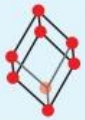
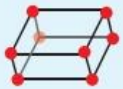


monoclinic
a = b ≠ c
$\alpha = \gamma = 90^o \; \beta \neq 90^o$



triclinic
a ≠ b ≠ c
$\alpha \neq \beta \neq \gamma \neq 90^o$

7 crystal system and 14 Bravais lattices

cubic	 primitive	 body centered	 face centered
tetragonal	 primitive	 body centered	
hexagonal			
orthorhombic	 primitive	 body centered	 face centered  basis face centered
monoclinic	 primitive		 basis face centered
trigonal			
triclinic			

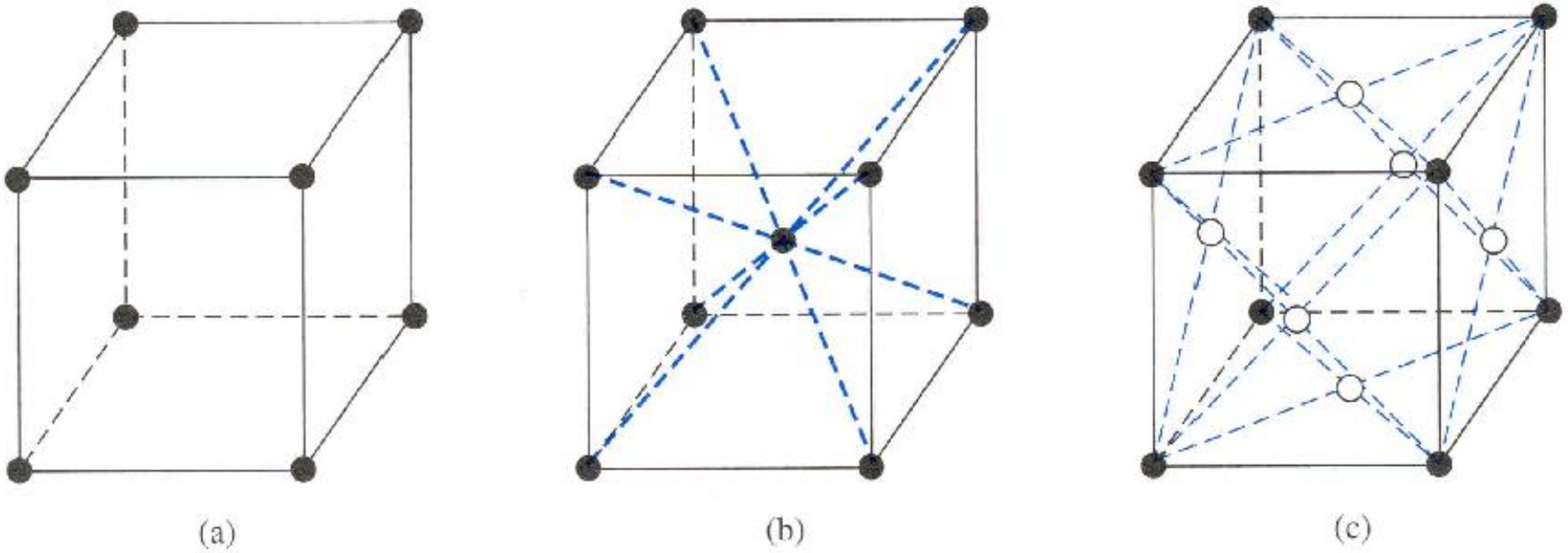
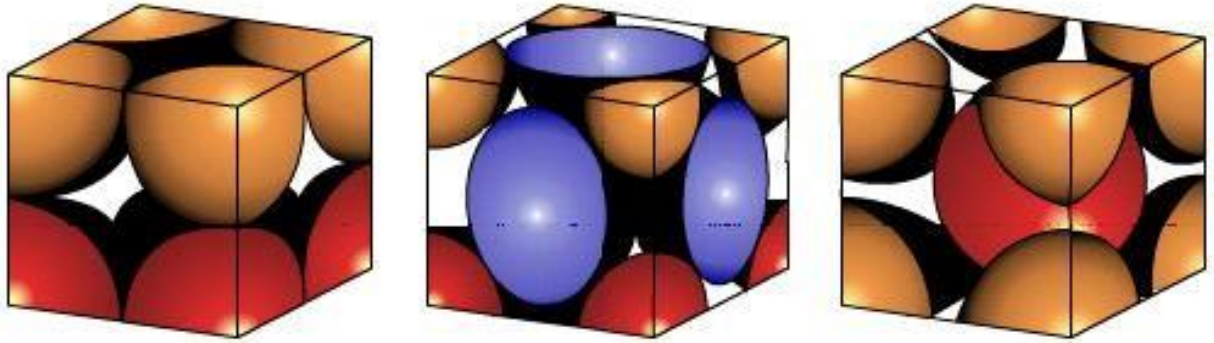


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

- simple cubic (sc)
- body-centered cubic (bcc)
- face-centered cubic (fcc)



(a) Simple cubic (b) Face centred cubic (c) Body centred cubic

Three dimensional view showing the number of atoms per unit cell

Unit cell	Number of atoms at			No. of atoms per unit cell	Volume occupied by particles (%)
	Corners	Centres	Faces		
Simple cubic	$8 \times \frac{1}{8} = 1$	0	0	1	52.4
Body centred cubic (BCC)	$8 \times \frac{1}{8} = 1$	1	0	2	68
Face centred cubic (FCC)	$8 \times \frac{1}{8} = 1$	0	$6 \times \frac{1}{2} = 3$	4	74

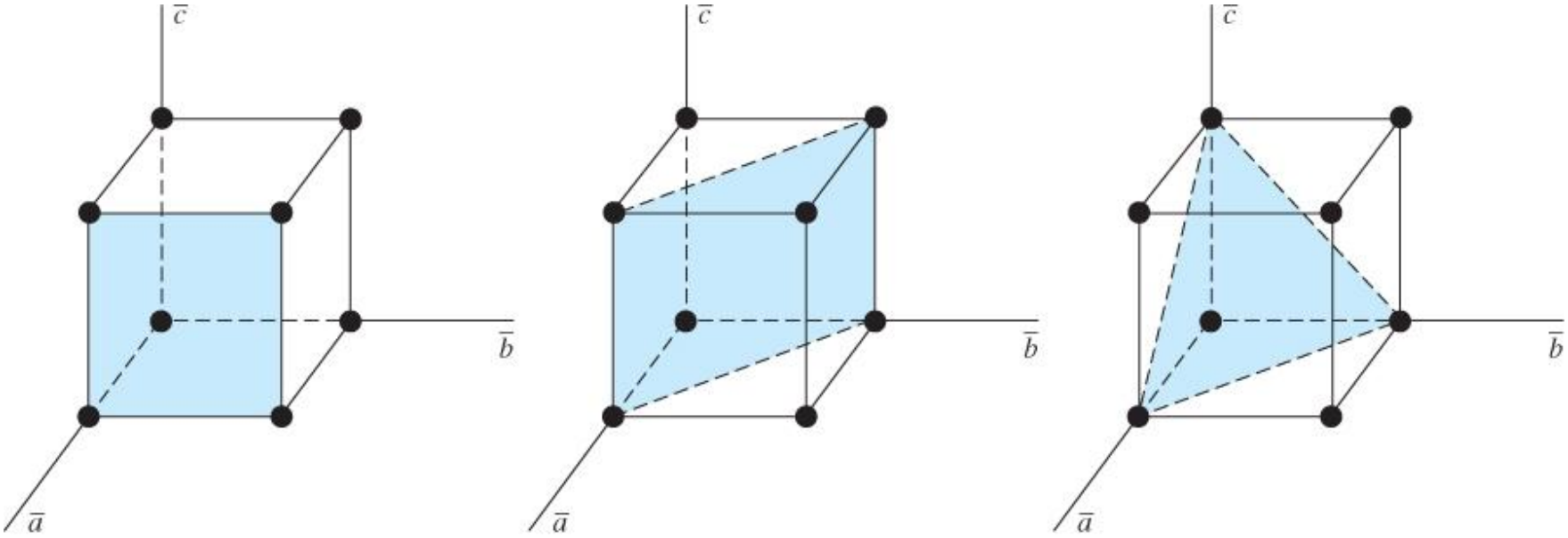


Figure 1.8 | Three lattice planes: (a) (100) plane, (b) (110) plane, (c) (111) plane.

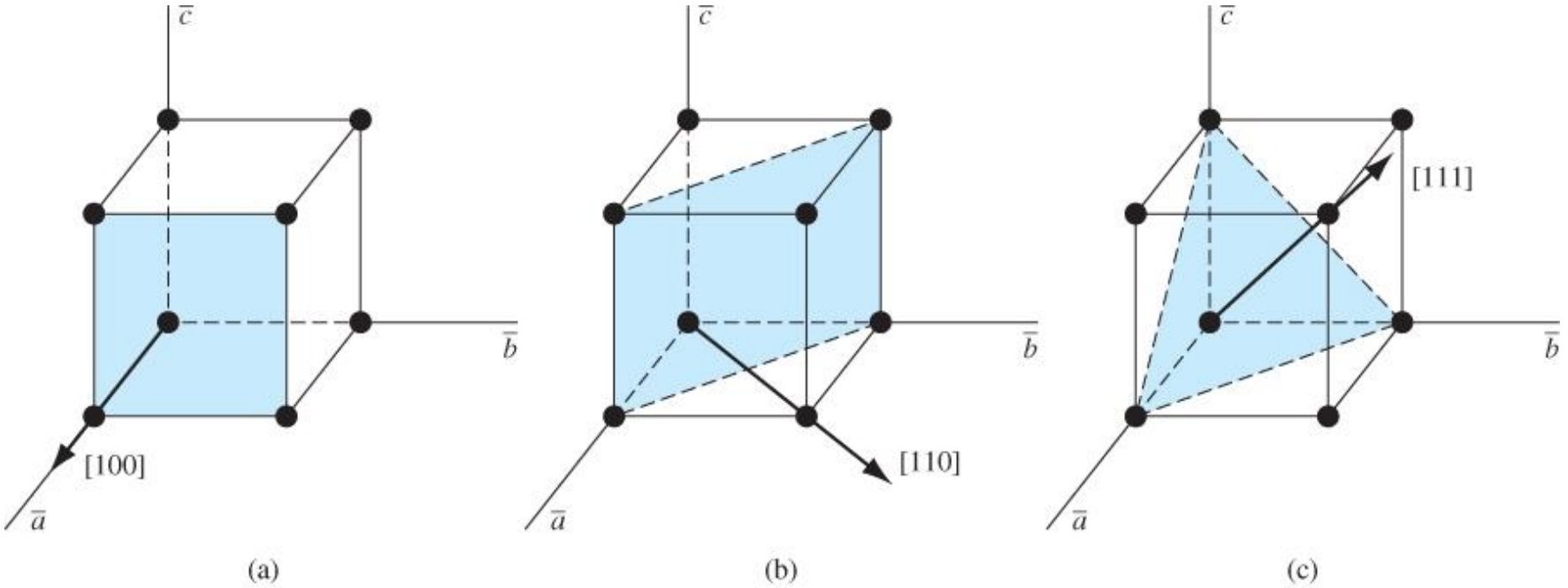
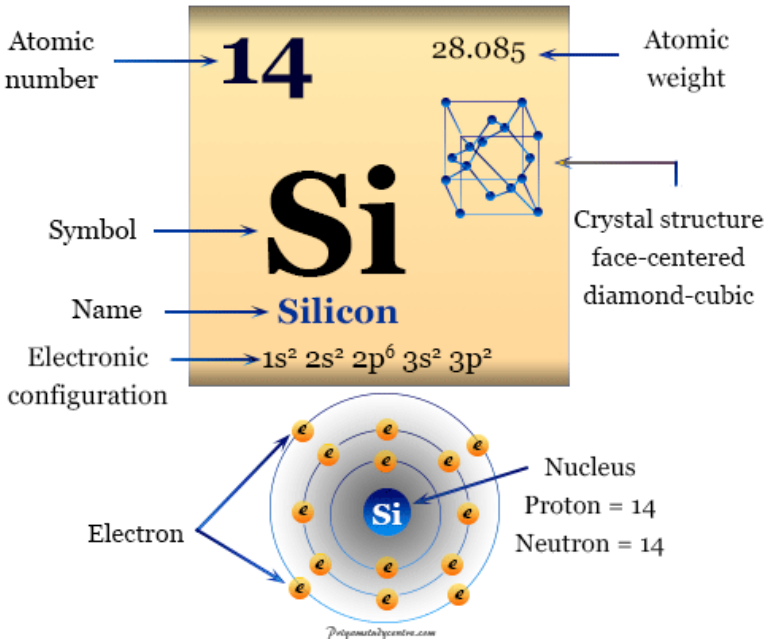
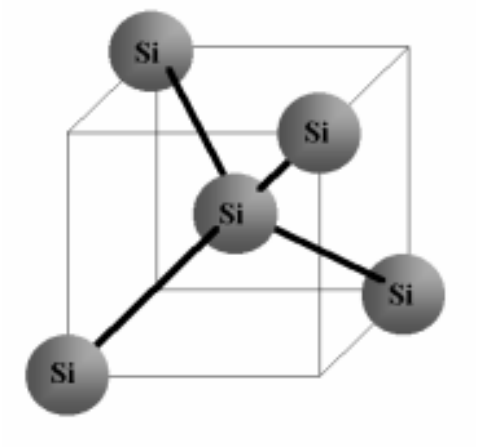
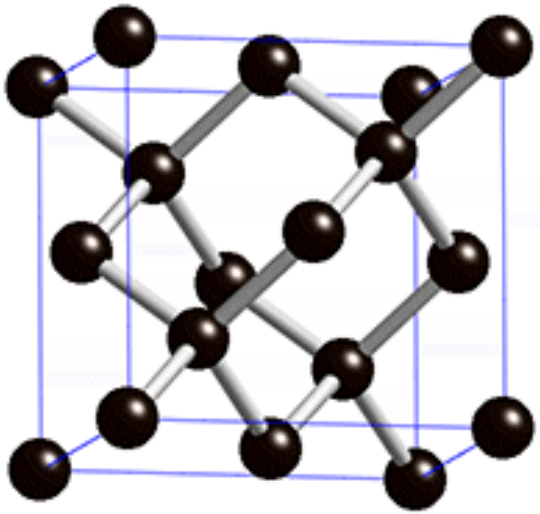


Figure 1.10 | Three lattice directions and planes: (a) (100) plane and [100] direction, (b) (110) plane and [110] direction, (c) (111) plane and [111] direction.







Diamond cubic structure

https://physicsopenlab.org/2018/01/28/silicon-germanium-crystal-structure/

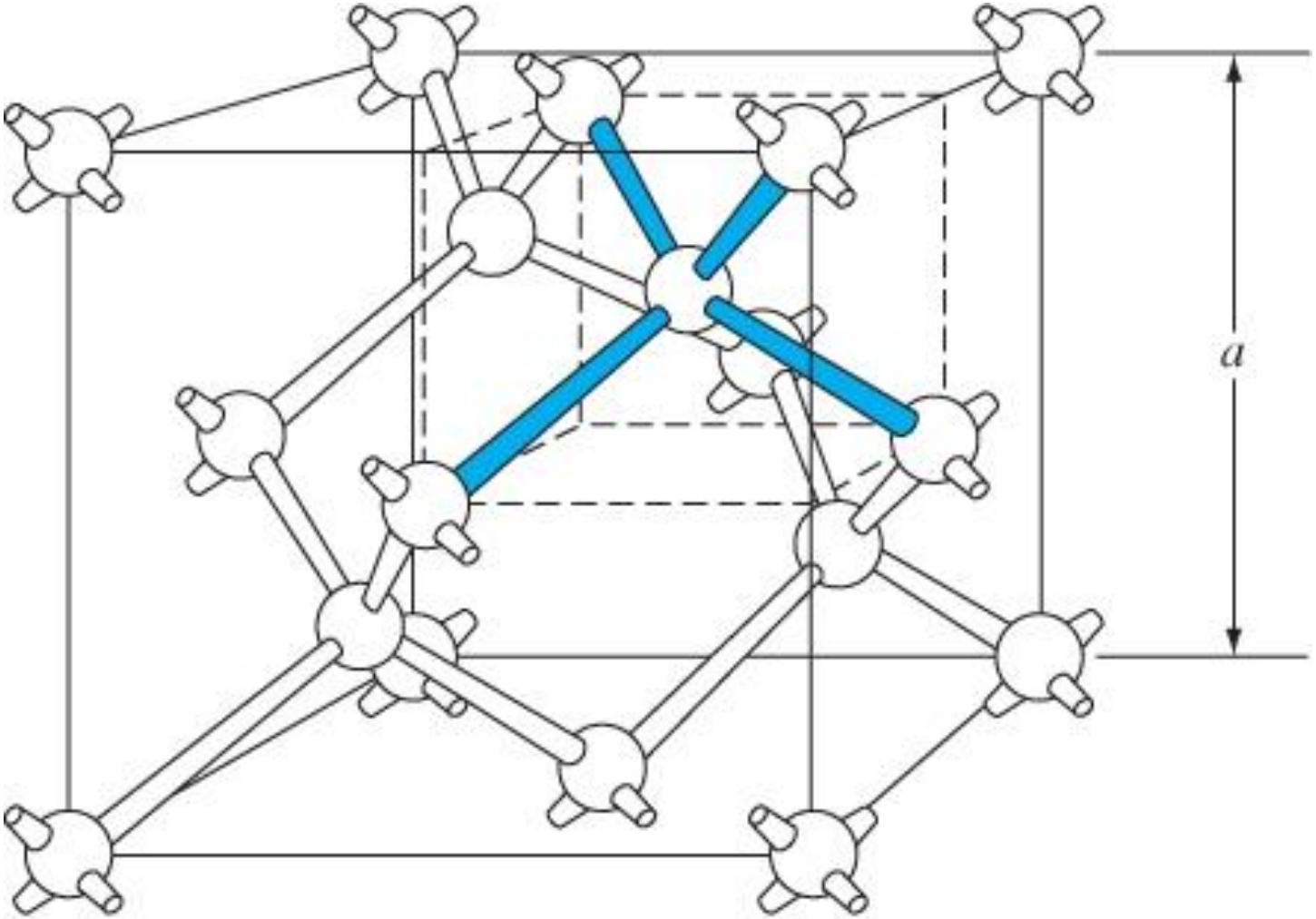


Figure 1.11 | The diamond structure.

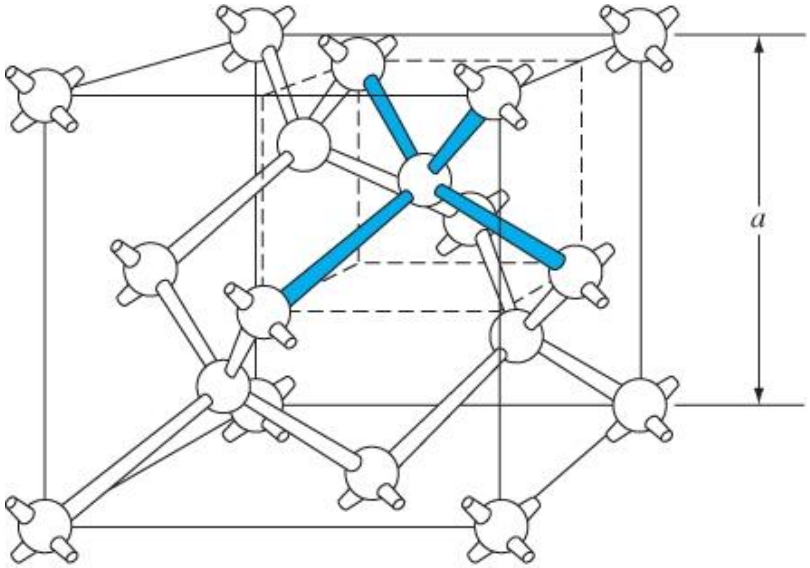
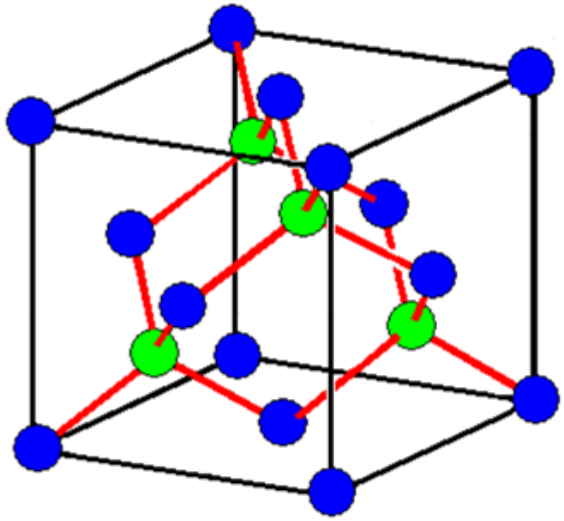
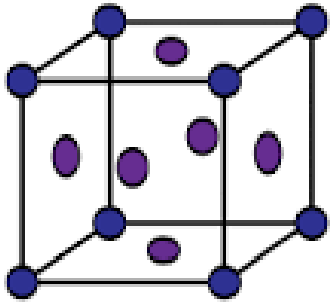
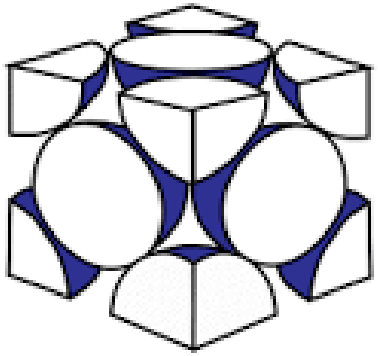


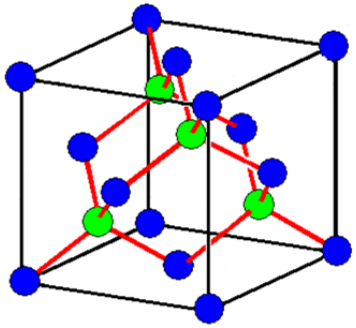
Figure 1.11 | The diamond structure.

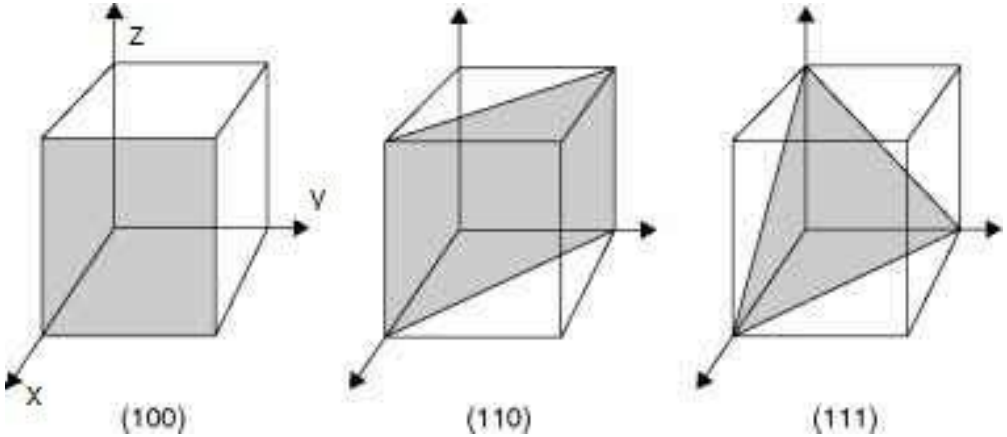


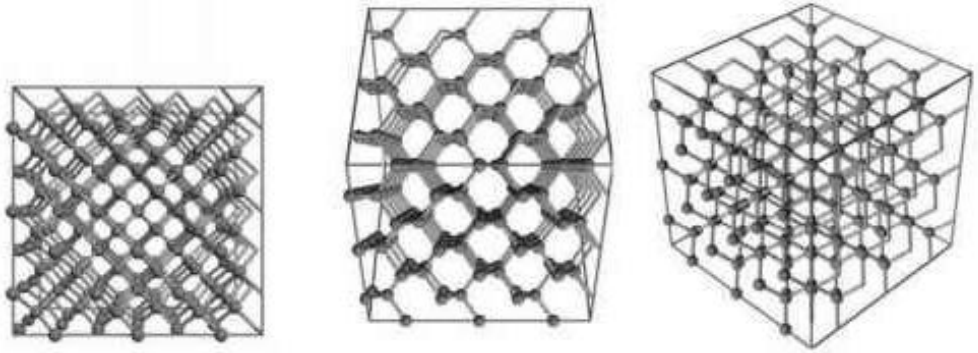
Two representations of FCC Crystal Structure








z
y
x
(100)
(110)
(111)



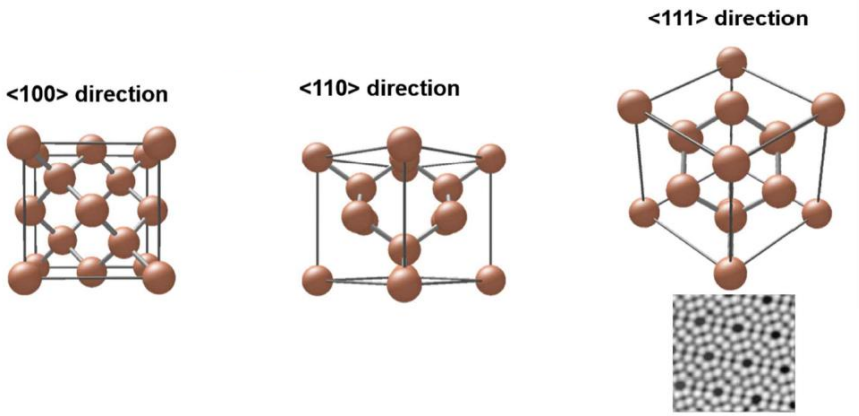
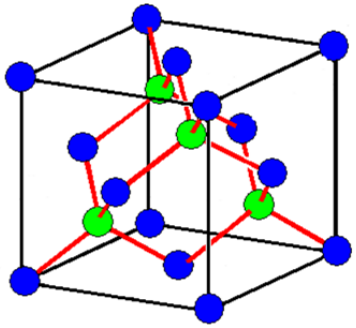
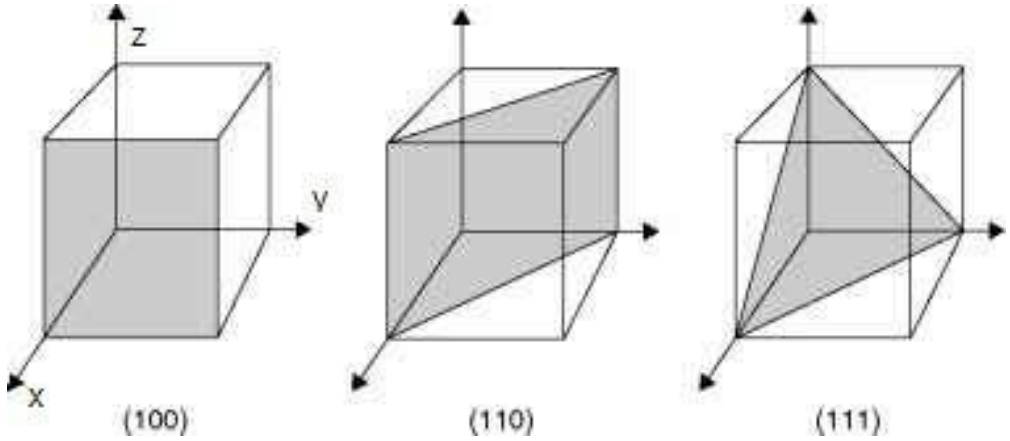

<100> direction
<110> direction
<111> direction

Figure 1.11





https://www.youtube.com/watch?v=vXk6Uhq74nU

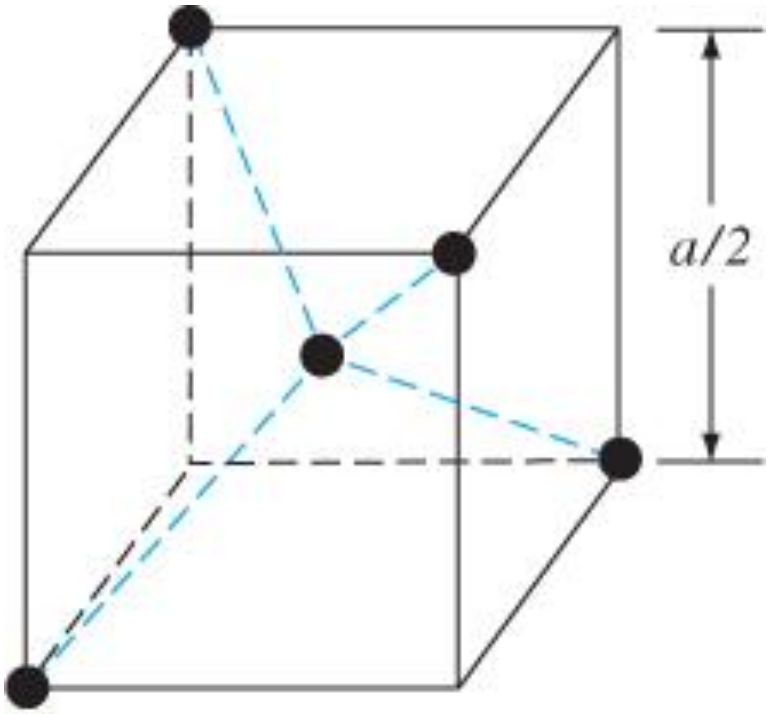
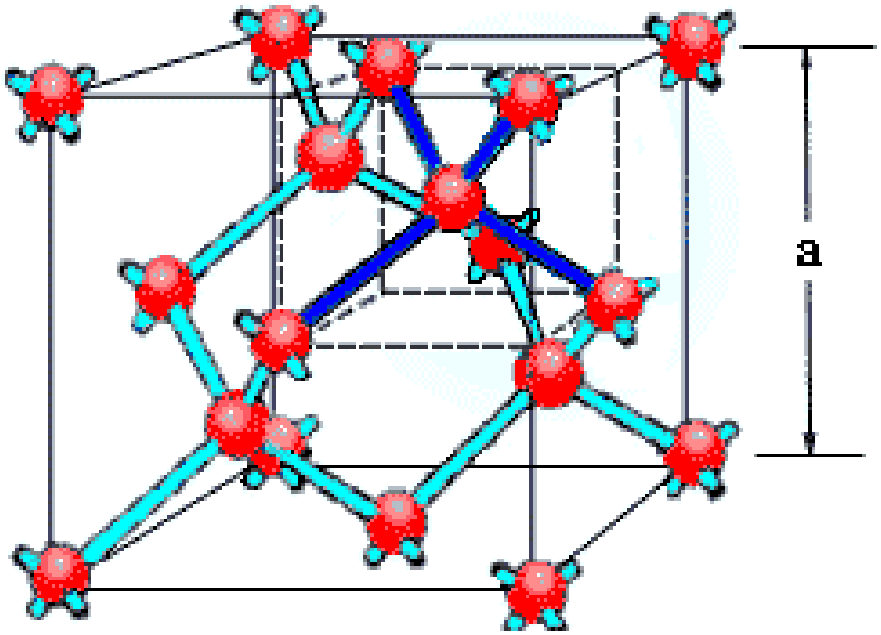
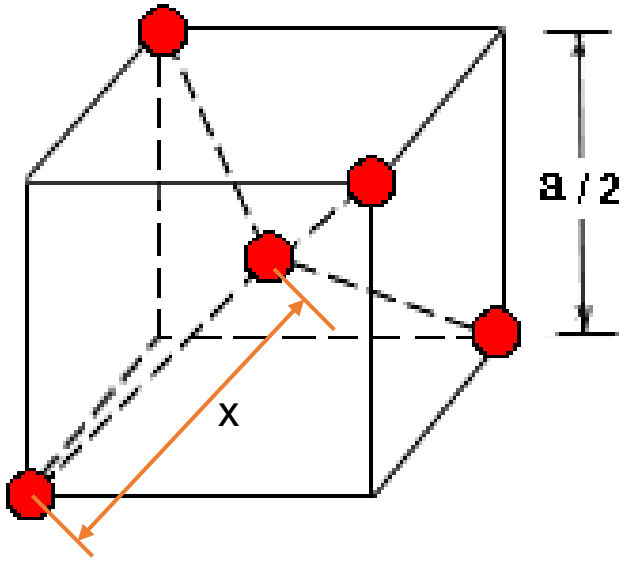


Figure 1.12 | The tetrahedral structure of closest neighbors in the diamond lattice.

a = lattice constant





Find the distance x between Si atoms. (@T = 300K, a of Si = 0.543 nm)

$$x = \sqrt{(\frac{\sqrt{2}}{4}a)^2 + (\frac{1}{4}a)^2}$$

$$x = \frac{\sqrt{3}}{4}a = 0.235nm$$

# of atoms = 8 a = 0.543 nm

volume density of Si = $8/a^3$ 5×10^{22} [#/cm^3]

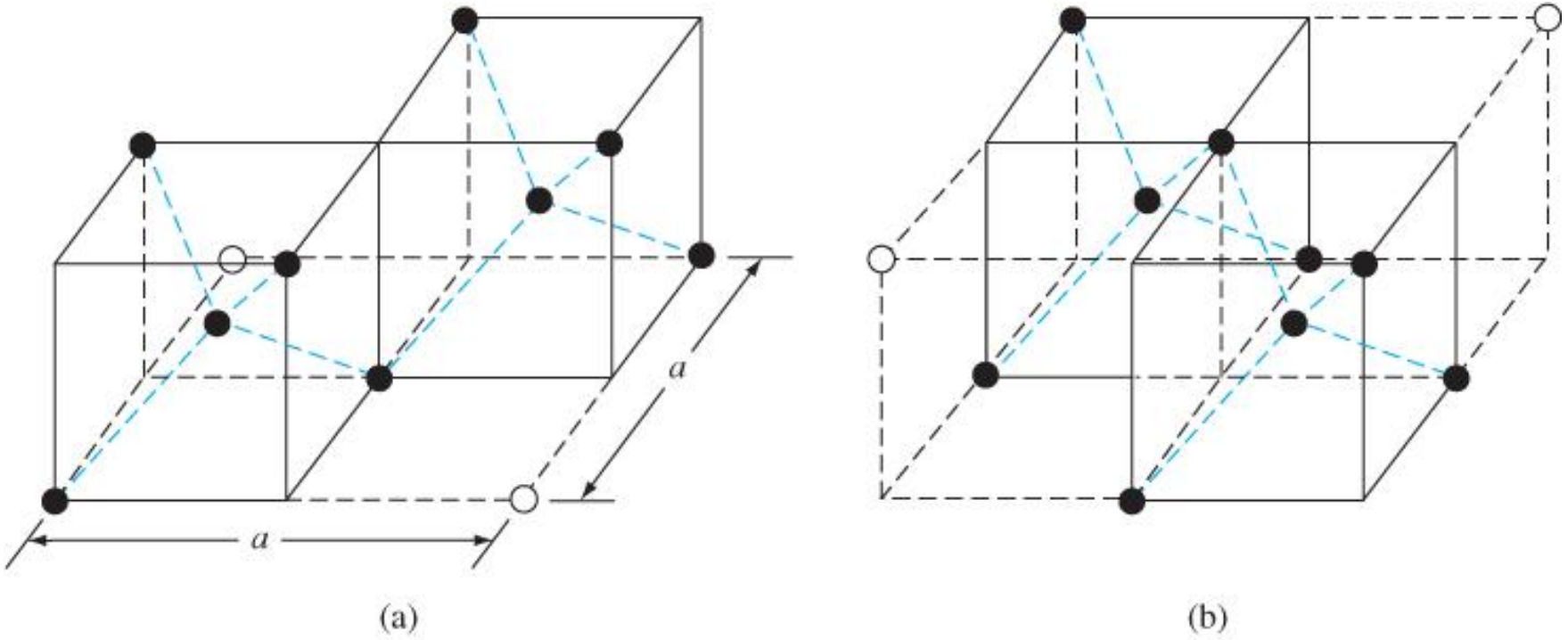


Figure 1.13 | Portions of the diamond lattice: (a) bottom half and (b) top half.

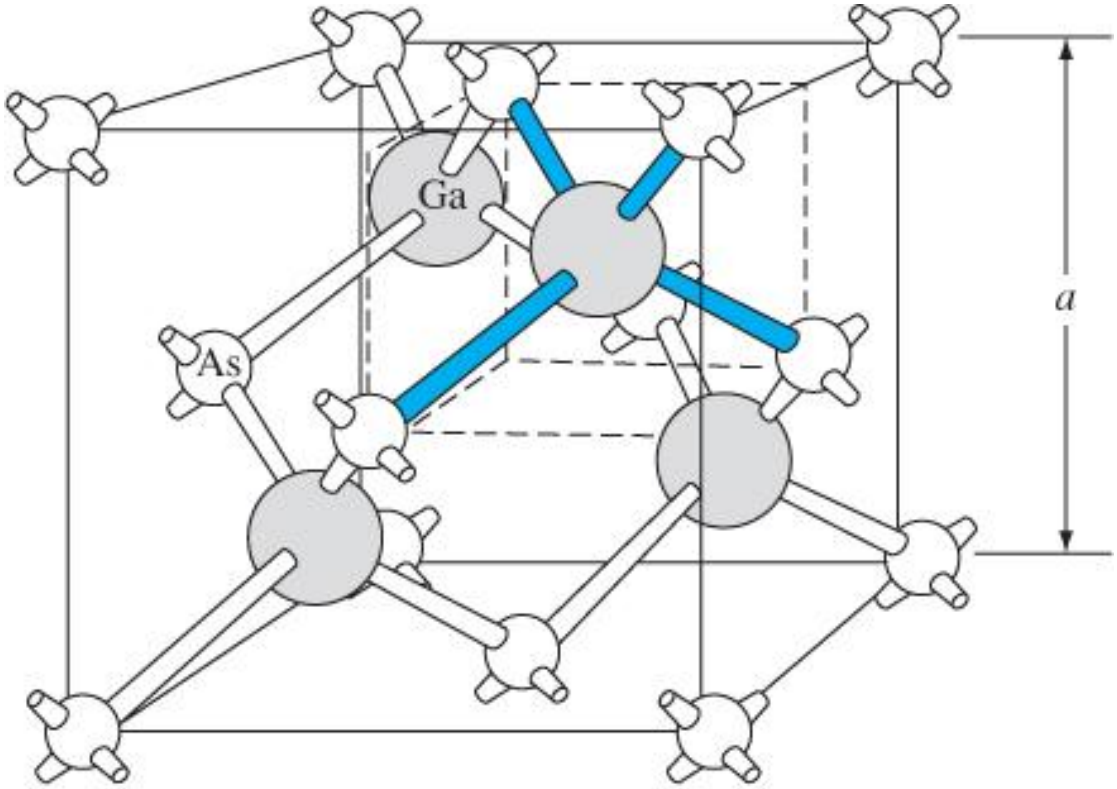


Figure 1.14 | The zincblende (sphalerite) lattice of GaAs.

GaAs, InP (Compound Semiconductors)

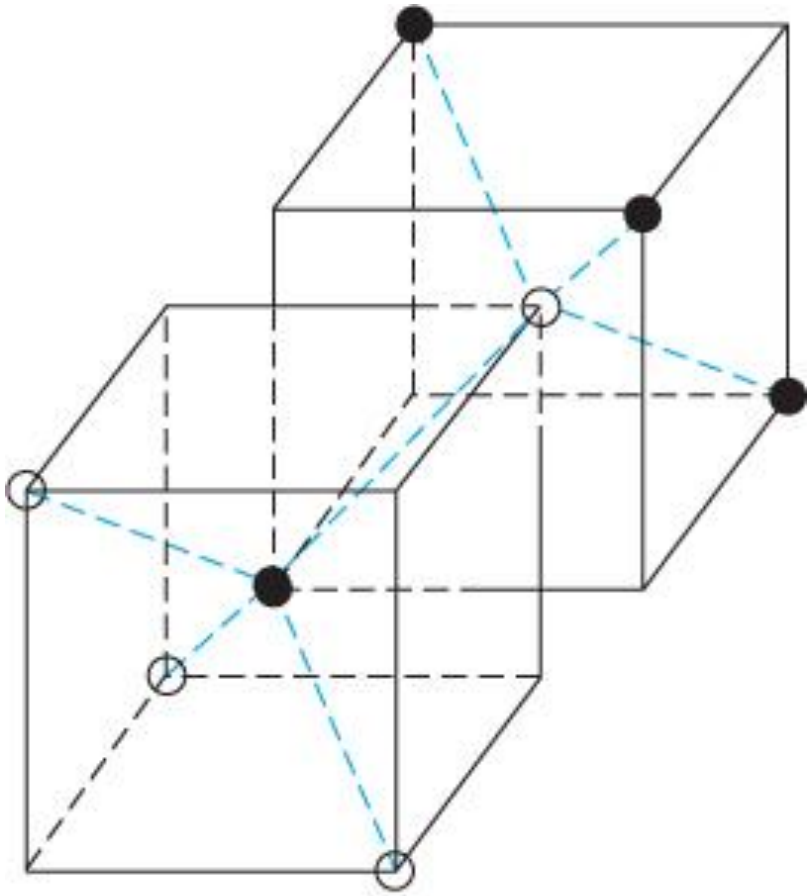


Figure 1.15 | The tetrahedral structure of closest neighbors in the zincblende lattice.

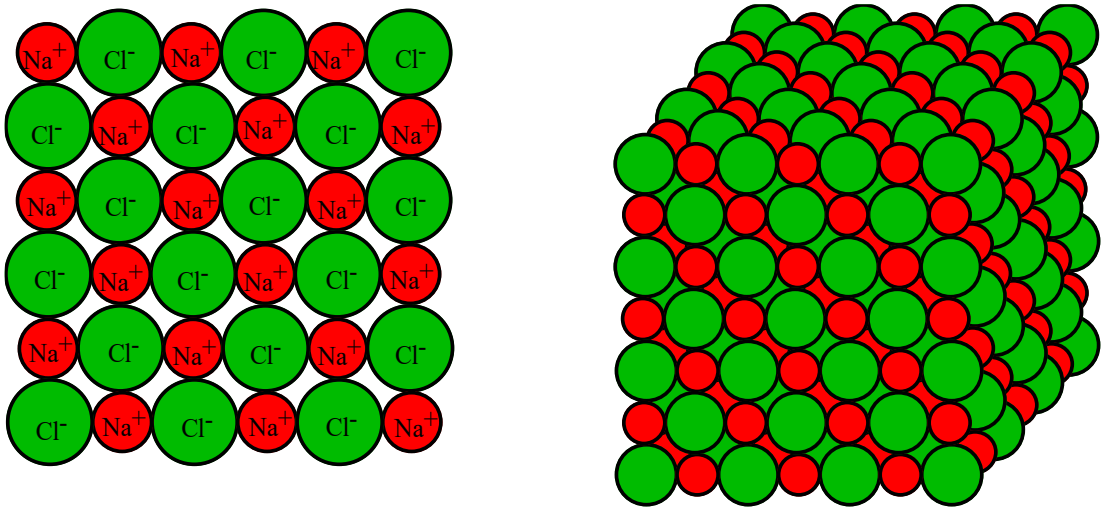


Fig. 1.9: (a) A schematic illustration of a cross section from solid NaCl. NaCl solid is made of Cl^- and Na^+ ions arranged alternatingly so that the oppositely charged ions are closest to each other and attract each other. There are also repulsive forces between the like-ions. In equilibrium the net force acting on any ion is zero. (b) Solid NaCl.

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- ionic bond

Figure 1.16 | Representation of (a) hydrogen valence electrons and (b) covalent bonding in a hydrogen molecule.

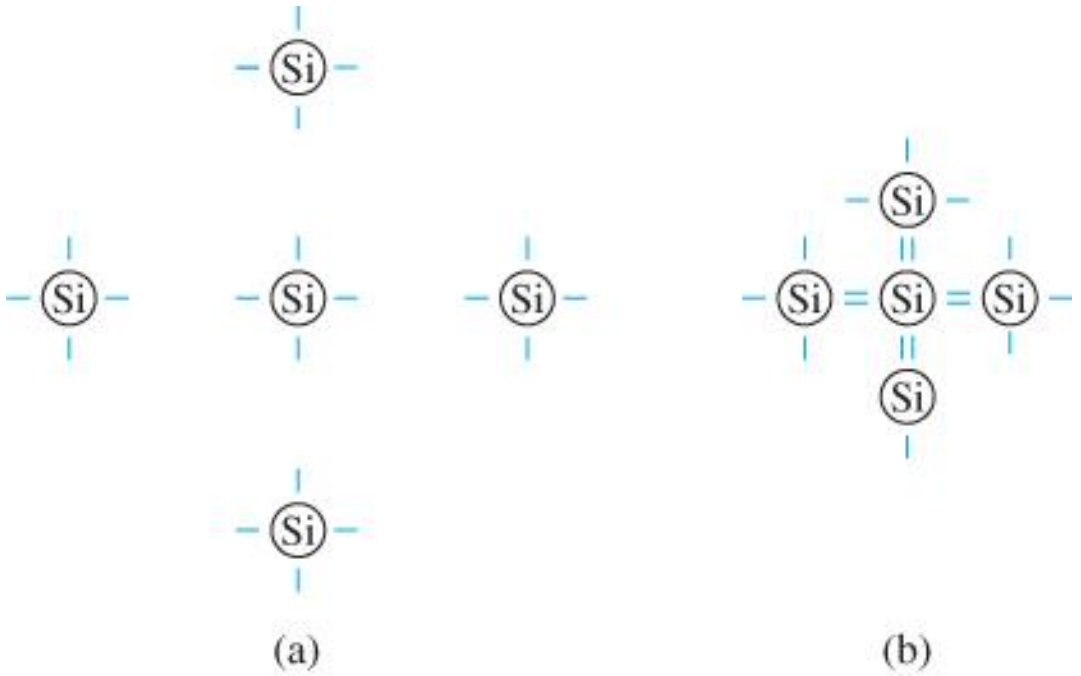

Figure 1.17 | Representation of (a) silicon valence electrons and (b) covalent bonding in the silicon crystal.

- covalent bonding

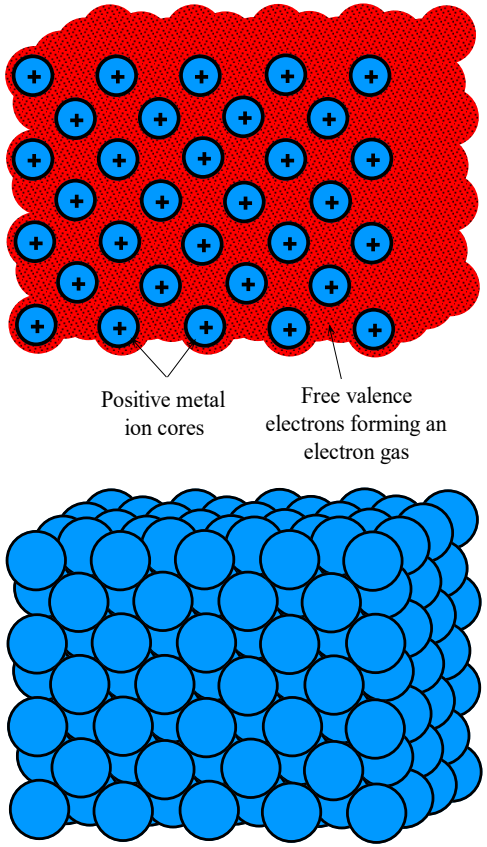

Fig. 1.7: In metallic bonding the valence electrons from the metal atoms form a "cloud of electrons" which fills the space between the metal ions and "glues" the ions together through the coulombic attraction between the electron gas and positive metal ions.

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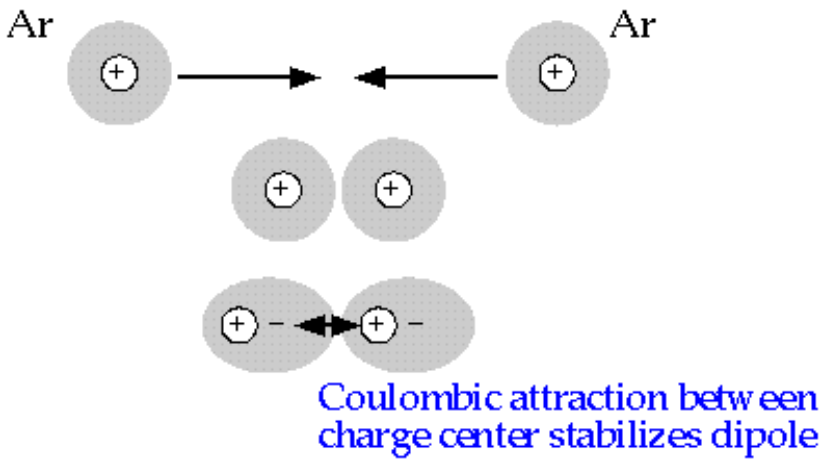
- metallic bonding



- van der Waals bond

Imperfections and Impurities in Solids

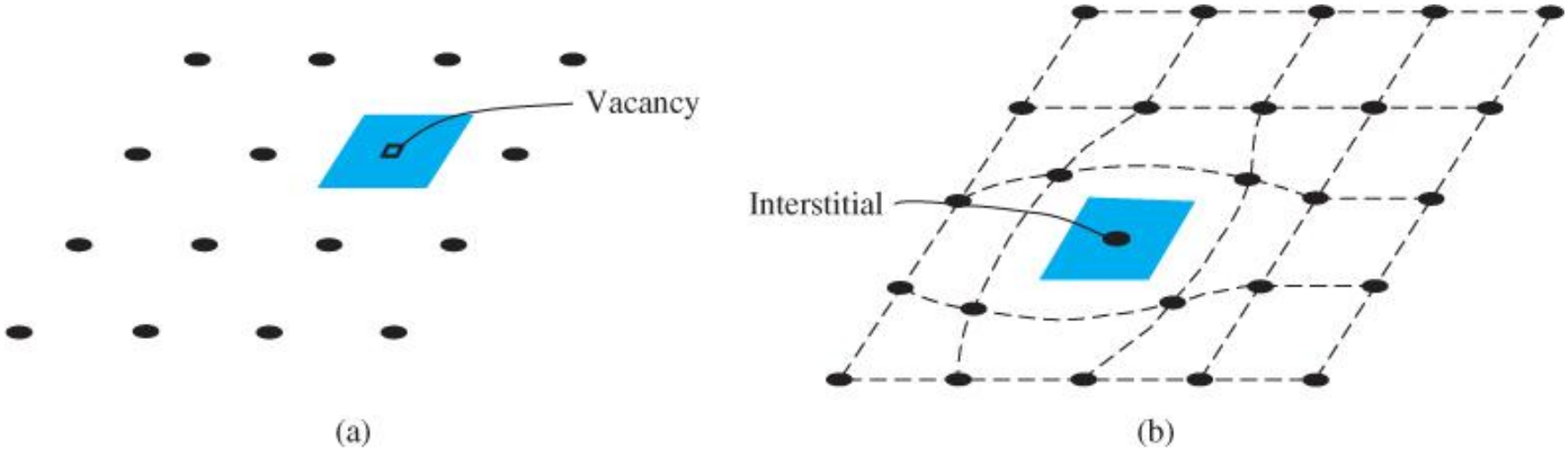


Figure 1.18 | Two-dimensional representation of a single-crystal lattice showing (a) a vacancy defect and (b) an interstitial defect.

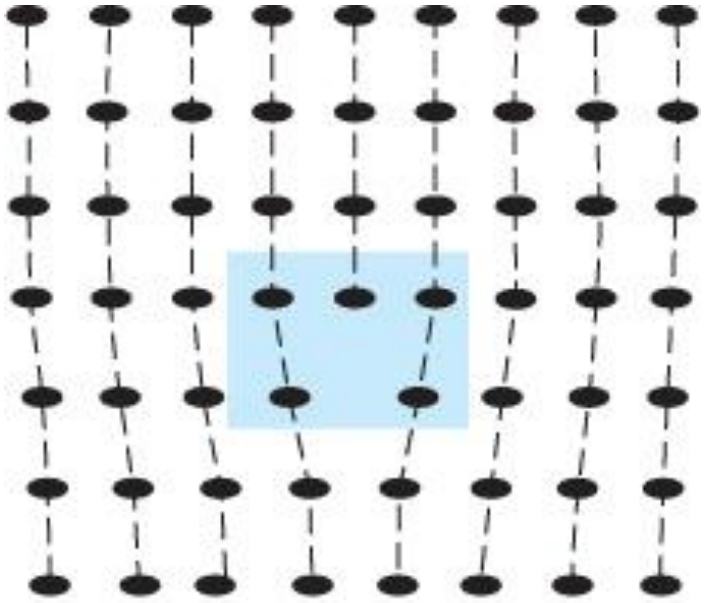
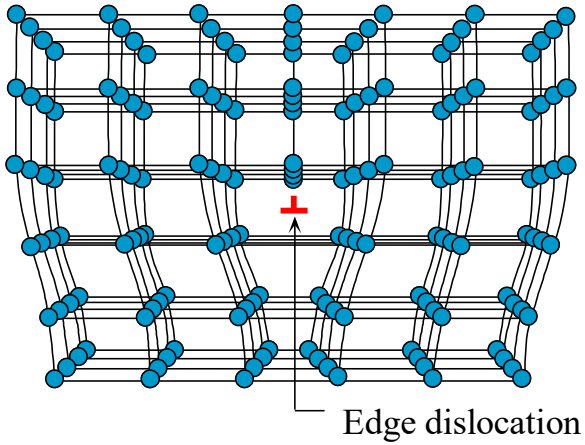
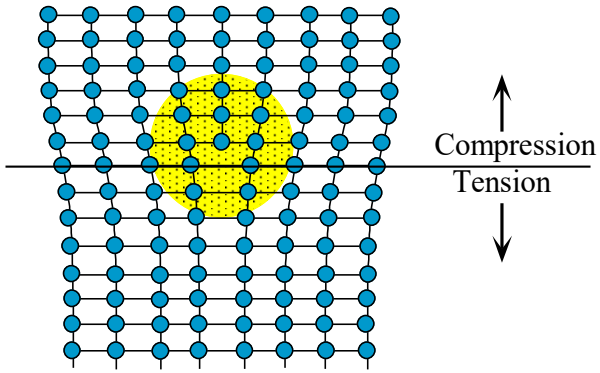


Figure 1.19 | A two-dimensional representation of a line dislocation.

line dislocation



(a) Dislocation is a line defect. The dislocation shown runs into the paper.



(b) Around the dislocation there is a strain field as the atomic bonds have been compressed above and stretched below the islocation line

Fig. 1.46: Dislocation in a crystal is a line defect which is accompanied by lattice distortion and hence a lattice strain around it.

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http://Materials.Usask.Ca

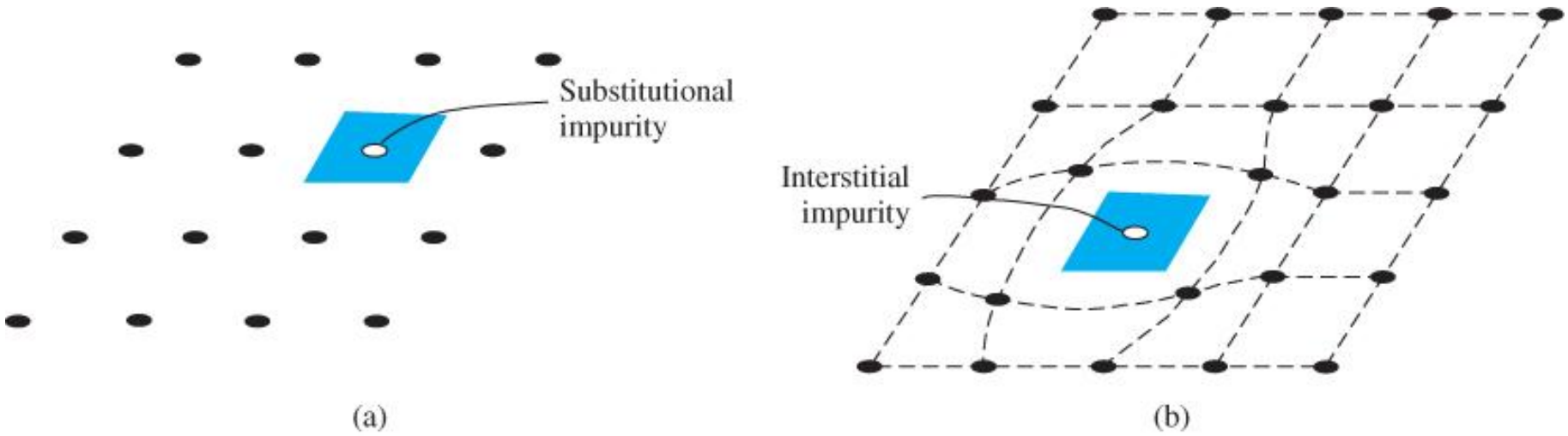


Figure 1.20 | Two-dimensional representation of a single-crystal lattice showing (a) a substitutional impurity and (b) an intersititial impurity.

- substitutional impurity
- interstitial impurity

- doping

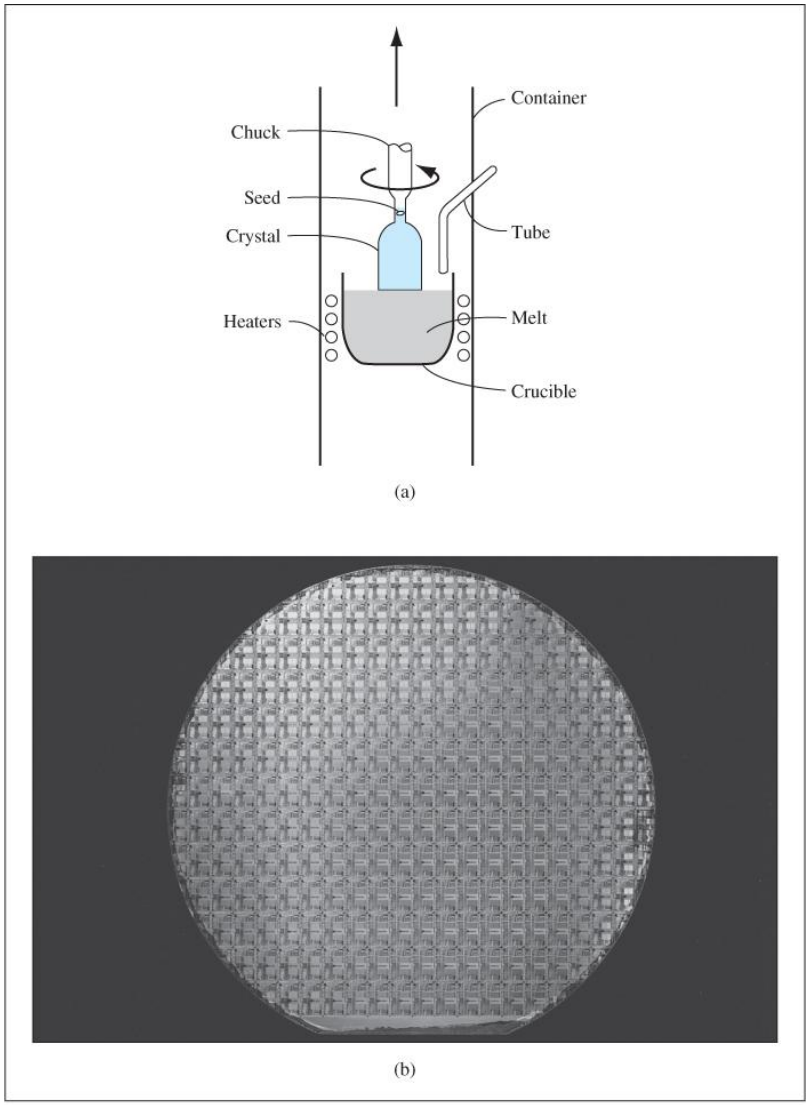
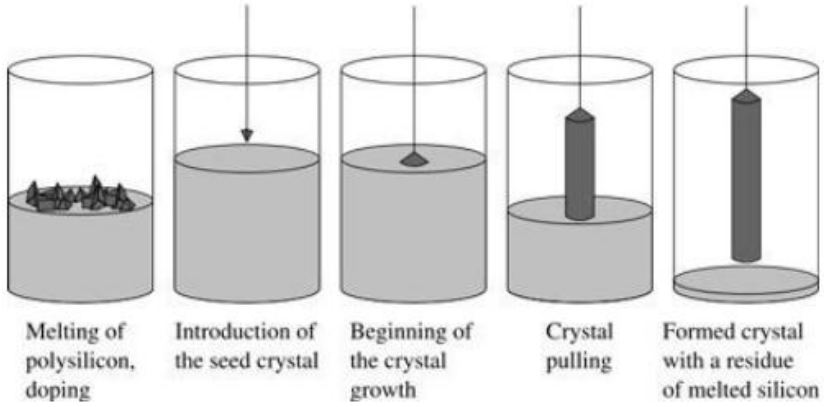


Figure 1.21 | (a) Model of a crystal puller and (b) photograph of a silicon wafer with an array of integrated circuits. The circuits are tested on the wafer then sawed apart into chips that are mounted into packages. (Photo courtesy of Intel Corporation.)

Czochralski method
→ Single crystal Si ingot



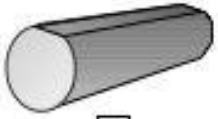
Preparation of Silicon Wafer

1. Crystal Growth

2. Single Crystal Ingot

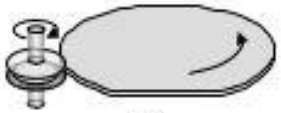
3. Crystal Trimming and Diameter Grind

4. Flat Grinding



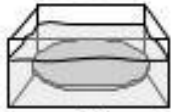
5. Wafer Slicing

6. Edge Rounding

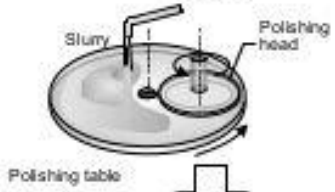


7. Lapping

8. Wafer Etching



9. Polishing



10. Wafer Inspection