
VE320 – Summer 2024

Introduction to Semiconductor Devices

Instructor: Yaping Dan (但亚平)
yaping.dan@sjtu.edu.cn

Chapter 1 Crystalline structure of solids



Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

1.5 Atomic bonding

1.6 Imperfections and impurities in solids

Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.1 Semiconductor materials

Resistivity:

Conductors	Semiconductors	Insulators
$< 10^{-3} \Omega\cdot\text{cm}$	$10^{-3} - 10^9 \Omega\cdot\text{cm}$	$> 10^9 \Omega\cdot\text{cm}$
Metals (Au, Al, Cu, Hg...)	Si, Ge, GaAs, InP...	SiO ₂ , HfO ₂ ...
Solids, liquids (Hg)	Solids	Solids, liquids gases

1.1 Semiconductor materials

Periodic Table of the Elements

IA

1

H

Hydrogen

1.008

1

2

IIA

Be

Beryllium

9.012

4

3

Li

Lithium

6.94

3

11

Na

Sodium

22.98976928

11

12

Mg

Magnesium

24.305

12

19

K

Potassium

39.0983

19

20

Ca

Calcium

40.078

20

37

Rb

Rubidium

85.4678

37

38

Sr

Strontium

87.62

38

55

Cs

Cesium

132.90545196

55

56

Ba

Barium

137.327

56

87

Fr

Francium

(223)

87

88

Ra

Radium

(226)

88

State of matter (color of name)

GAS LIQUID SOLID UNKNOWN

Subcategory in the metal-metalloid-nonmetal trend (color of background)

Alkali metals Alkaline earth metals Transition metals Lanthanides Actinides Post-transition metals Metalloids Reactive nonmetals Noble gases Unknown chemical properties

Atomic Number →

1

← Symbol

H

← Atomic Weight

1.008

1

← Electrons per shell

1

12

IIIA

B

Boron

10.81

5

13

Al

Aluminum

26.98

13

14

Si

Silicon

28.085

14

15

P

Phosphorus

30.974

15

16

S

Sulfur

32.06

16

17

Cl

Chlorine

35.45

17

18

Ar

Argon

39.948

18

25

Mn

Manganese

54.938044

25

26

Fe

Iron

55.845

26

27

Co

Cobalt

58.933

27

28

Ni

Nickel

58.693

28

29

Cu

Copper

63.546

29

30

Zn

Zinc

65.38

30

31

Ga

Gallium

69.723

31

32

Ge

Germanium

72.630

32

33

As

Arsenic

74.922

33

34

Se

Selenium

78.971

34

35

Br

Bromine

79.904

35

36

Kr

Krypton

83.798

36

41

Nb

Niobium

92.90637

41

42

Mo

Molybdenum

95.95

42

43

Tc

Technetium

(98)

43

44

Ru

Ruthenium

101.07

44

45

Rh

Rhodium

102.91

45

46

Pd

Palladium

106.42

46

47

Ag

Silver

107.87

47

48

Cd

Cadmium

112.41

48

49

In

Indium

114.82

49

50

Sn

Tin

118.71

50

51

Sb

Antimony

121.76

51

52

Te

Tellurium

127.60

52

53

I

Iodine

126.90

53

54

Xe

Xenon

131.29

54

72

Hf

Hafnium

178.49

72

73

Ta

Tantalum

180.94788

73

74

W

Tungsten

183.84

74

75

Re

Rhenium

186.21

75

76

Os

Osmium

190.23

76

77

Ir

Iridium

192.22

77

78

Pt

Platinum

195.08

78

79

Au

Gold

196.97

79

80

Hg

Mercury

200.59

80

81

Tl

Thallium

204.38

81

82

Pb

Lead

207.2

82

83

Bi

Bismuth

208.98

83

84

Po

Polonium

(209)

84

85

At

Astatine

(210)

85

86

Rn

Radon

(222)

86

104

Rf

Rutherfordium

(261)

104

105

Db

Dubnium

(268)

105

106

Sg

Seaborgium

(269)

106

107

Bh

Bohrium

(270)

107

108

Hs

Hassium

(271)

108

109

Mt

Meitnerium

(272)

109

110

Ds

Darmstadtium

(281)

110

111

Rg

Roentgenium

(282)

111

112

Cn

Copernicium

(285)

112

113

Nh

Nihonium

(284)

113

114

Fl

Flerovium

(289)

114

115

Mc

Moscovium

(290)

115

116

Lv

Livermorium

(293)

116

117

Ts

Tennessine

(294)

117

118

Og

Oganesson

(294)

118

57

La

Lanthanum

138.91

57

58

Ce

Cerium

140.12

58

59

Pr

Praseodymium

140.91

59

60

Nd

Neodymium

144.24

60

61

Pm

Promethium

(145)

61

62

Sm

Samarium

150.36

62

63

Eu

Europium

151.96

63

64

Gd

Gadolinium

157.25

64

65

Tb

Terbium

158.93

65

66

Dy

Dysprosium

162.50

66

67

Ho

Holmium

164.93

67

68

Er

Erbium

167.26

68

69

Tm

Thulium

168.93

69

70

Yb

Ytterbium

173.05

70

71

Lu

Lutetium

174.97

71

89

Ac

Actinium

(227)

89

90

Th

Thorium

232.04

90

91

Pa

Protactinium

231.04

91

92

U

Uranium

238.03

92

93

Np

Neptunium

(237)

93

94

Pu

Plutonium

(244)

94

95

Am

Americium

(243)

95

96

Cm

Curium

(247)

96

97

Bk

Berkelium

(247)

97

98

Cf

Californium

(251)

98

99

Es

Einsteinium

(252)

99

100

Fm

Fermium

(257)

100

101

Md

Mendelevium

(258)

101

102

No

Nobelium

(259)

102

103

Lr

Lawrencium

(260)

103

1.1 Semiconductor materials

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

1.1 Semiconductor materials

Periodic Table of the Elements

<div><div>Atomic Number → 1 ← Symbol</div><div>Name → Hydrogen ← Atomic Weight</div><div>Electrons per shell → 1</div></div>																		<div><div>State of matter (color of name)</div><div>GAS LIQUID SOLID UNKNOWN</div></div>																		<div><div>Subcategory in the metal-metalloid-nonmetal trend (color of background)</div><div>Alkali metals Lanthanides Metalloids</div><div>Alkaline earth metals Actinides Reactive nonmetals</div><div>Transition metals Post-transition metals Noble gases</div></div>																		<div>Unknown chemical properties</div>																																																																																																																																																																																																																																																																													
<div>1 IA H Hydrogen 1.008 1</div>																		<div>2 IIA He Helium 4.0026 2</div>																		<div>3 Li Lithium 6.94 3</div>																		<div>4 Be Beryllium 9.0122 4</div>																		<div>5 B Boron 10.81 5</div>																		<div>6 C Carbon 12.01 6</div>																		<div>7 N Nitrogen 14.007 7</div>																		<div>8 O Oxygen 15.999 8</div>																		<div>9 F Fluorine 18.998 9</div>																		<div>10 Ne Neon 20.180 10</div>																																																																																																																																																																	
<div>11 Na Sodium 22.98976928 11</div>																		<div>12 Mg Magnesium 24.305 12</div>																		<div>13 Al Aluminum 26.982 13</div>																		<div>14 Si Silicon 28.085 14</div>																		<div>15 P Phosphorus 30.974 15</div>																		<div>16 S Sulfur 32.06 16</div>																		<div>17 Cl Chlorine 35.45 17</div>																		<div>18 Ar Argon 39.948 18</div>																																																																																																																																																																																																					
<div>19 K Potassium 39.0983 19</div>																		<div>20 Ca Calcium 40.078 20</div>																		<div>21 Sc Scandium 44.955908 21</div>																		<div>22 Ti Titanium 47.88 22</div>																		<div>23 V Vanadium 50.9415 23</div>																		<div>24 Cr Chromium 51.9961 24</div>																		<div>25 Mn Manganese 54.938044 25</div>																		<div>26 Fe Iron 55.845 26</div>																		<div>27 Co Cobalt 58.933 27</div>																		<div>28 Ni Nickel 58.693 28</div>																		<div>29 Cu Copper 63.546 29</div>																		<div>30 Zn Zinc 65.38 30</div>																		<div>31 Ga Gallium 69.723 31</div>																		<div>32 Ge Germanium 72.630 32</div>																		<div>33 As Arsenic 74.922 33</div>																		<div>34 Se Selenium 78.971 34</div>																		<div>35 Br Bromine 79.904 35</div>																		<div>36 Kr Krypton 83.798 36</div>																	
<div>37 Rb Rubidium 85.4678 37</div>																		<div>38 Sr Strontium 87.62 38</div>																		<div>39 Y Yttrium 88.90584 39</div>																		<div>40 Zr Zirconium 91.224 40</div>																		<div>41 Nb Niobium 92.90637 41</div>																		<div>42 Mo Molybdenum 95.95 42</div>																		<div>43 Tc Technetium (98) 98</div>																		<div>44 Ru Ruthenium 101.07 44</div>																		<div>45 Rh Rhodium 102.91 45</div>																		<div>46 Pd Palladium 106.42 46</div>																		<div>47 Ag Silver 107.87 47</div>																		<div>48 Cd Cadmium 112.41 48</div>																		<div>49 In Indium 114.82 49</div>																		<div>50 Sn Tin 118.71 50</div>																		<div>51 Sb Antimony 121.76 51</div>																		<div>52 Te Tellurium 127.60 52</div>																		<div>53 I Iodine 126.90 53</div>																		<div>54 Xe Xenon 131.29 54</div>																	
<div>55 Cs Cesium 132.90545196 55</div>																		<div>56 Ba Barium 137.327 56</div>																		<div>57-71 Lanthanides</div>																		<div>72 Hf Hafnium 178.49 72</div>																		<div>73 Ta Tantalum 180.94788 73</div>																		<div>74 W Tungsten 183.84 74</div>																		<div>75 Re Rhenium 186.21 75</div>																		<div>76 Os Osmium 190.23 76</div>																		<div>77 Ir Iridium 192.22 77</div>																		<div>78 Pt Platinum 195.08 78</div>																		<div>79 Au Gold 196.967 79</div>																		<div>80 Hg Mercury 200.59 80</div>																		<div>81 Tl Thallium 204.38 81</div>																		<div>82 Pb Lead 207.2 82</div>																		<div>83 Bi Bismuth 208.98 83</div>																		<div>84 Po Polonium (209) 209</div>																		<div>85 At Astatine (210) 210</div>																		<div>86 Rn Radon (222) 222</div>																	
<div>87 Fr Francium (223) 223</div>																		<div>88 Ra Radium (226) 226</div>																		<div>89-103 Actinides</div>																		<div>104 Rf Rutherfordium (261) 261</div>																		<div>105 Db Dubnium (268) 268</div>																		<div>106 Sg Seaborgium (266) 266</div>																		<div>107 Bh Bohrium (264) 264</div>																		<div>108 Hs Hassium (277) 277</div>																		<div>109 Mt Meitnerium (268) 268</div>																		<div>110 Ds Darmstadtium (281) 281</div>																		<div>111 Rg Roentgenium (282) 282</div>																		<div>112 Cn Copernicium (285) 285</div>																		<div>113 Nh Nihonium (284) 284</div>																		<div>114 Fl Flerovium (289) 289</div>																		<div>115 Mc Moscovium (288) 288</div>																		<div>116 Lv Livermorium (293) 293</div>																		<div>117 Ts Tennessine (294) 294</div>																		<div>118 Og Oganesson (294) 294</div>																	
<div>57 La Lanthanum 138.91 57</div>																		<div>58 Ce Cerium 140.12 58</div>																		<div>59 Pr Praseodymium 140.91 59</div>																		<div>60 Nd Neodymium 144.24 60</div>																		<div>61 Pm Promethium (145) 145</div>																		<div>62 Sm Samarium 150.36 62</div>																		<div>63 Eu Europium 151.96 63</div>																		<div>64 Gd Gadolinium 157.25 64</div>																		<div>65 Tb Terbium 158.93 65</div>																		<div>66 Dy Dysprosium 162.50 66</div>																		<div>67 Ho Holmium 164.93 67</div>																		<div>68 Er Erbium 167.26 68</div>																		<div>69 Tm Thulium 168.93 69</div>																		<div>70 Yb Ytterbium 173.05 70</div>																		<div>71 Lu Lutetium 174.97 71</div>																																																																							
<div>89 Ac Actinium (227) 227</div>																		<div>90 Th Thorium 232.04 90</div>																		<div>91 Pa Protactinium 231.04 91</div>																		<div>92 U Uranium 238.03 92</div>																		<div>93 Np Neptunium (237) 237</div>																		<div>94 Pu Plutonium (244) 244</div>																		<div>95 Am Americium (243) 243</div>																		<div>96 Cm Curium (247) 247</div>																		<div>97 Bk Berkelium (247) 247</div>																		<div>98 Cf Californium (251) 251</div>																		<div>99 Es Einsteinium (252) 252</div>																		<div>100 Fm Fermium (257) 257</div>																		<div>101 Md Mendelevium (258) 258</div>																		<div>102 No Nobelium (259) 259</div>																		<div>103 Lr Lawrencium (260) 260</div>																																																																							

1.1 Semiconductor materials

Conductivity of semiconductors:

- ☐ Tunable by static electric field
 - MOSFET: metal oxide semiconductor field effect transistors
- ☐ Susceptible to impurities
 - Intrinsic silicon: $214000 \Omega \cdot \text{cm}$ at 300K
 - Doped with phosphorus (1ppm): $0.2 \Omega \cdot \text{cm}$ at 300K
- ☐ Sensitive to light illumination

1.1 Semiconductor materials

Semiconductors are the materials that have resistivities between $10^{-3} - 10^9 \Omega\cdot\text{cm}$ depending on light illumination, temperature, electric field, magnetic field and impurities.

Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

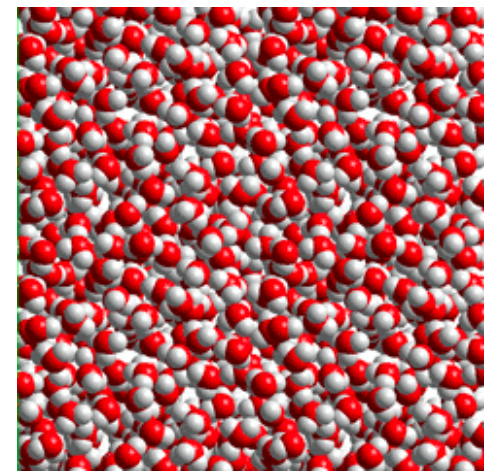
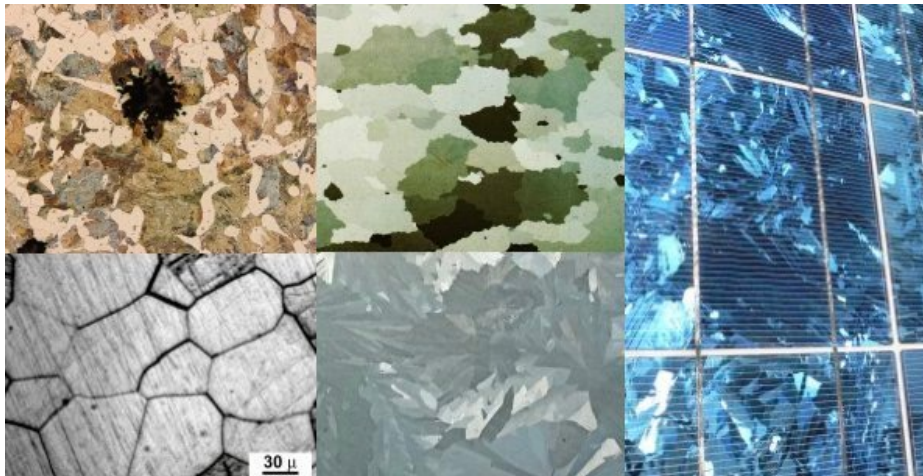
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.2 Type of Solids

Solids:

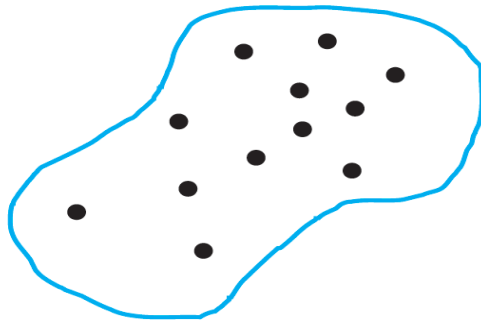
- Single crystals
- Polycrystals
- Amorphous



1.2 Type of Solids

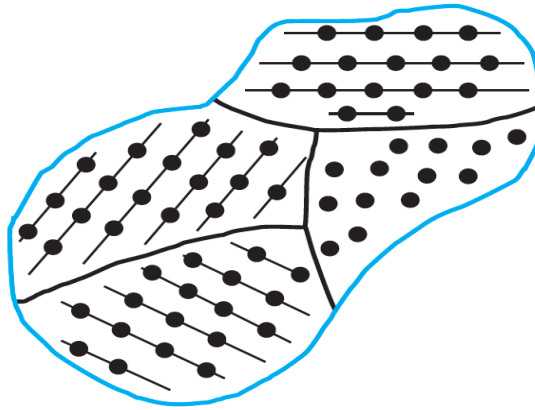
Solids :

- Amorphous
- Polycrystals
- Single crystals



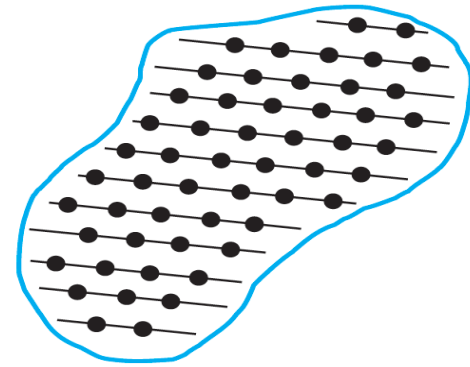
(a)

All atoms or ions are periodically ranged in a short range (a few atoms)



(b)

Multiple crystalline grains randomly packed



(c)

All atoms or ions are periodically ranged in a long range (μm scale)

1.2 Type of Solids

Characteristics of Crystals

- Specific shape and fixed melting point
- Atoms or ions periodically arranged in a relatively large scale (μm)

All semiconductors covered in this course are assumed to be single crystalline.

Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

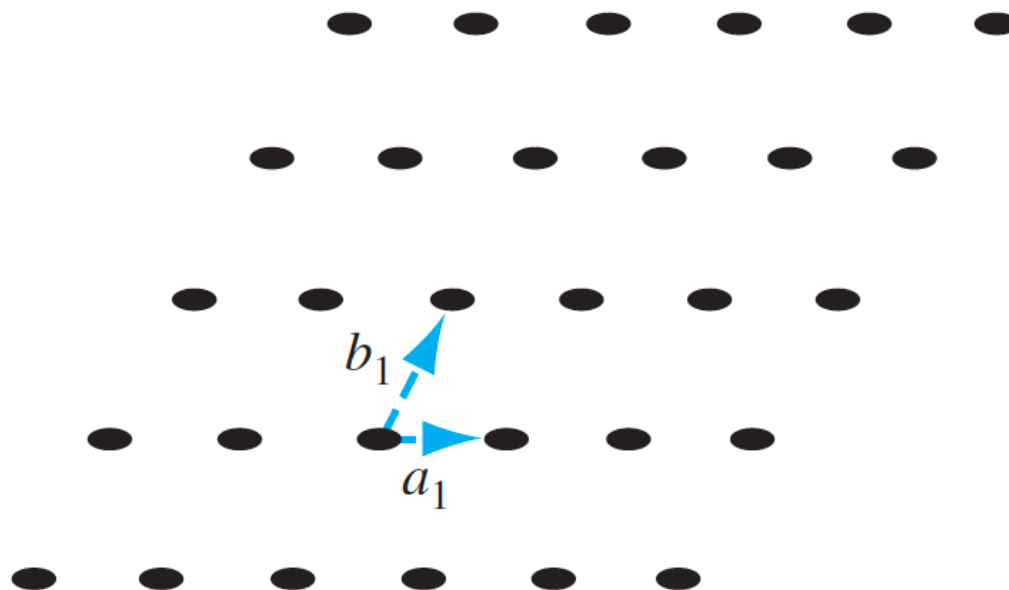
1.4 The diamond structure

1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.3 Space lattice

Primitive and Unit Cell

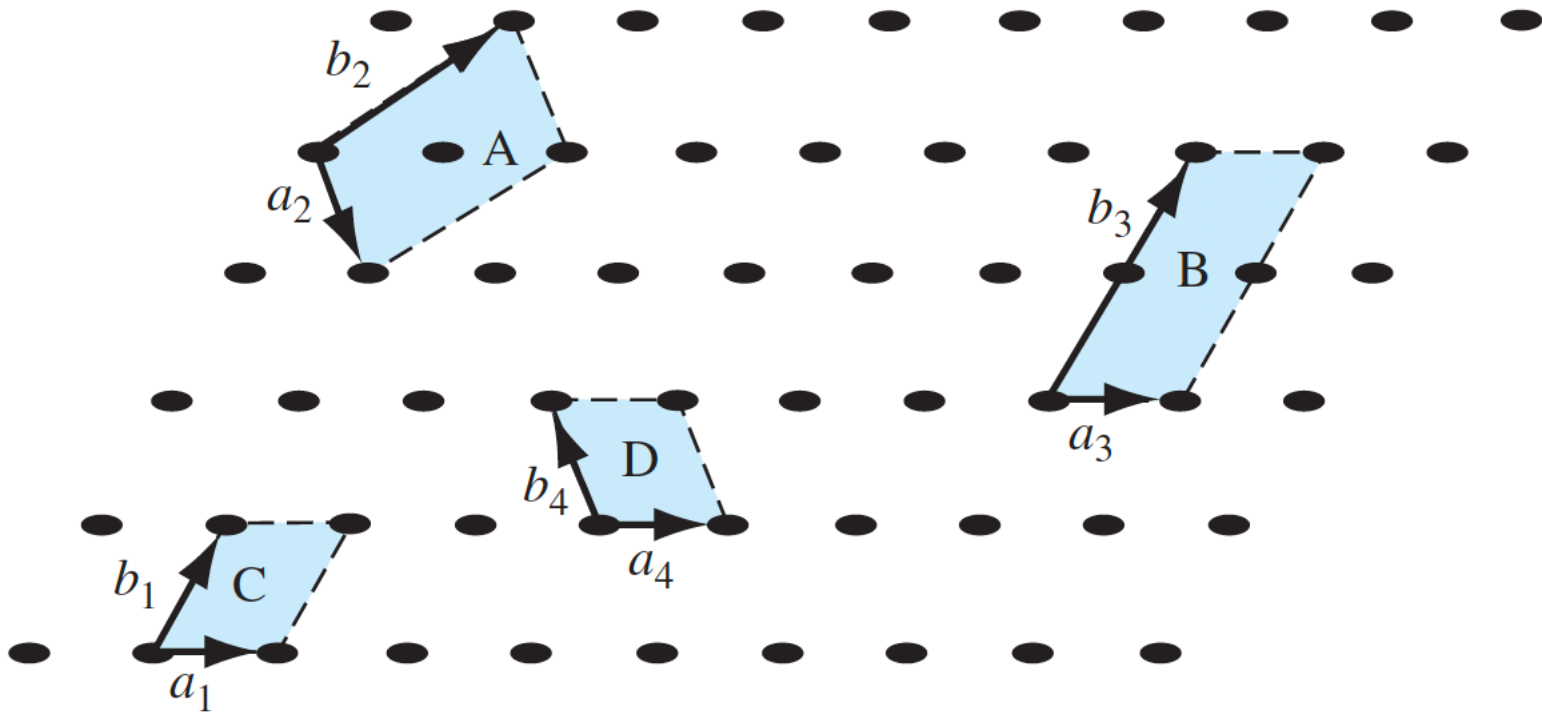


Unit cell: any small volume of crystal to reproduce the entire crystal.

Primitive cell: smallest unit cell

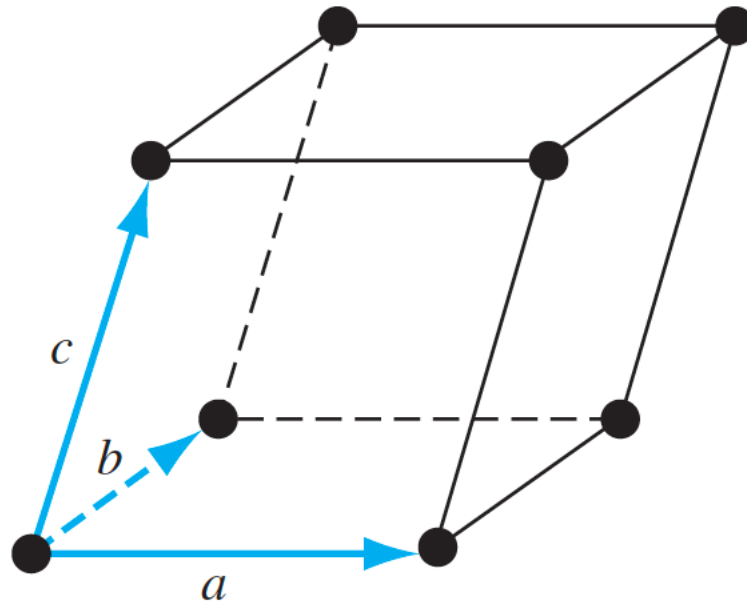
1.3 Space lattice

Primitive and Unit Cell



1.3 Space lattice

Primitive and Unit Cell



$$\vec{r} = p\vec{a} + q\vec{b} + s\vec{c}$$

A generalized primitive unit cell

1.3 Space lattice

Basic Crystal Structures

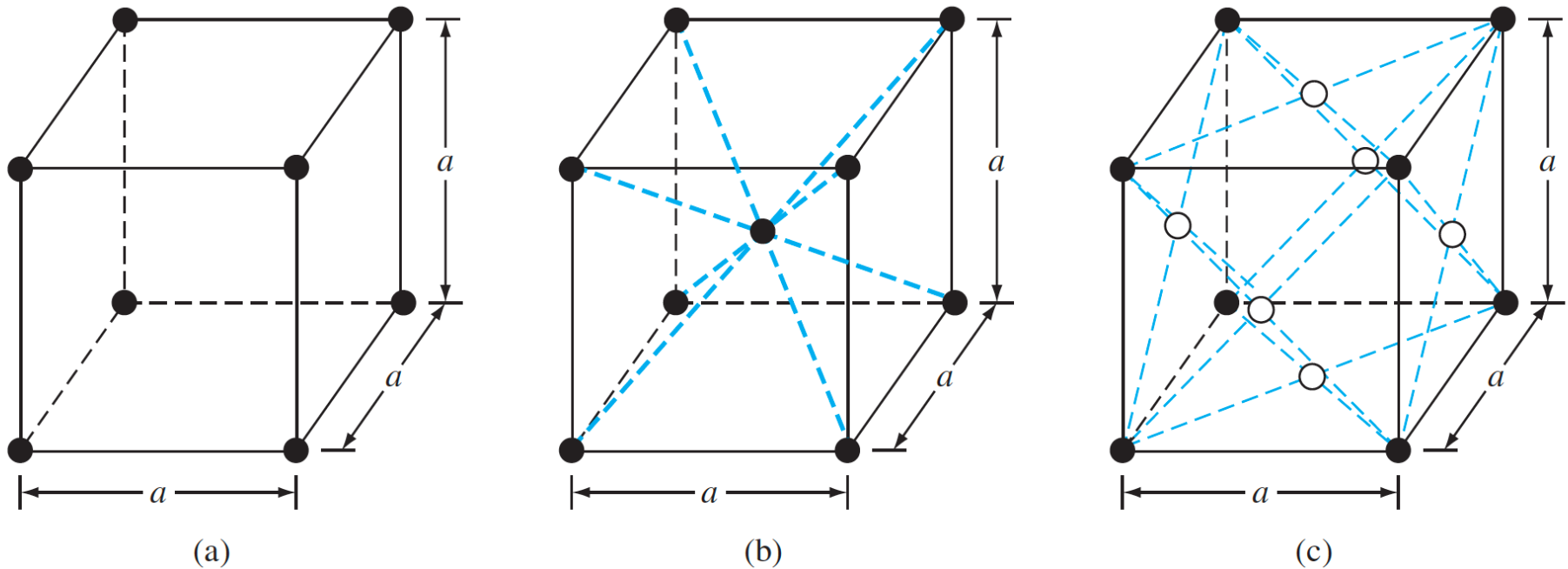


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

1.3 Space lattice

Basic Crystal Structures: volume density of atoms

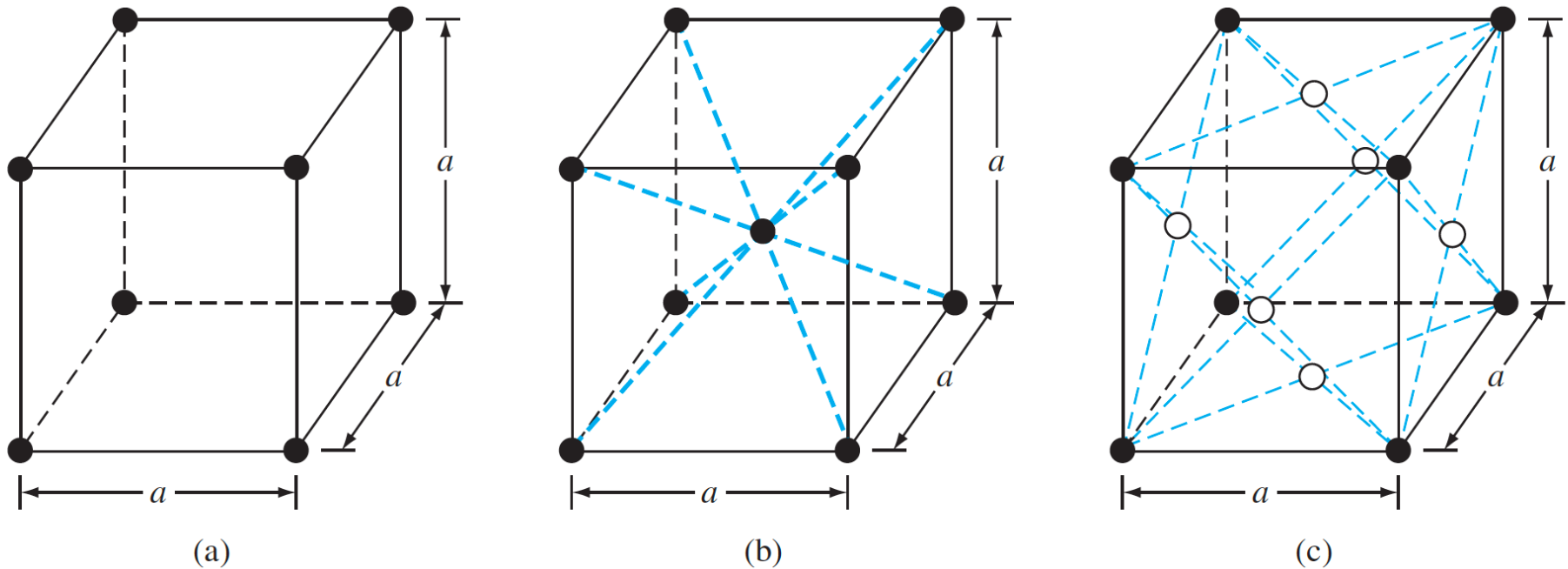
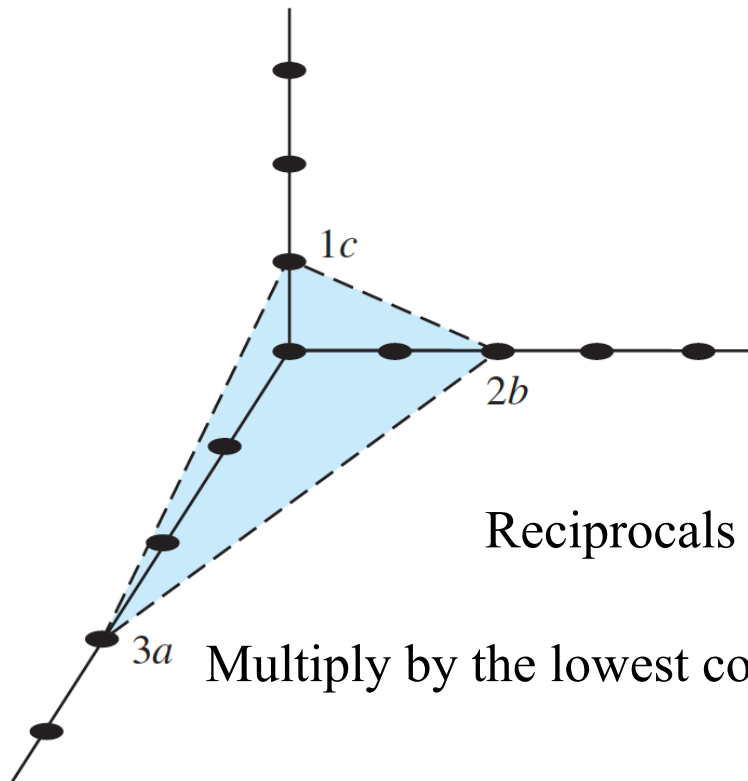


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

1.3 Space lattice

Crystalline Plane and Miller Index

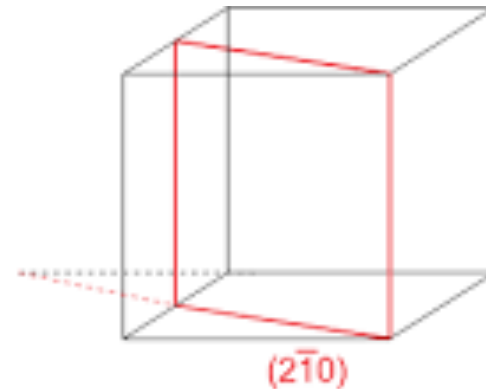
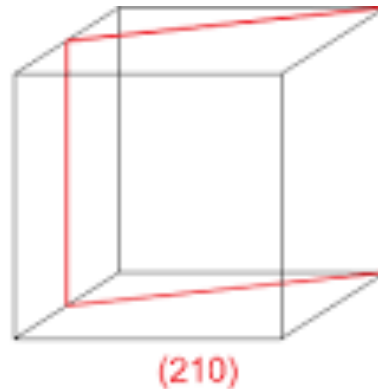
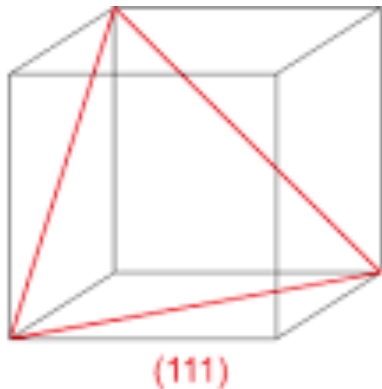
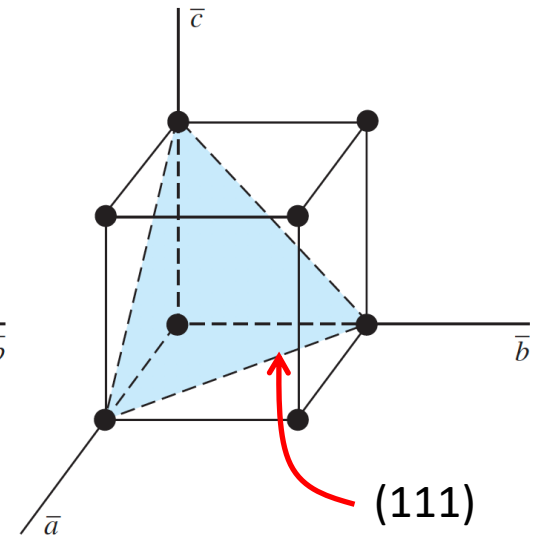
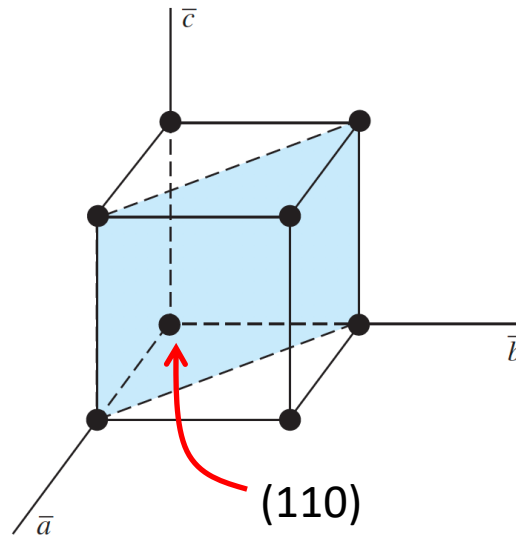
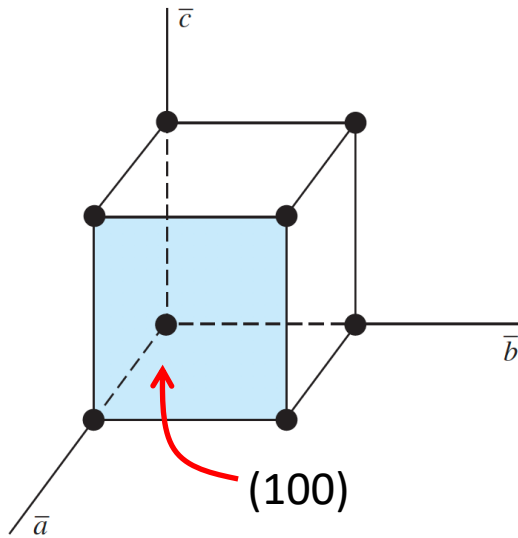


Reciprocals of the intercepts: $(1/3, 1/2, 1)$

Multiply by the lowest common denominator: $(2, 3, 6)$

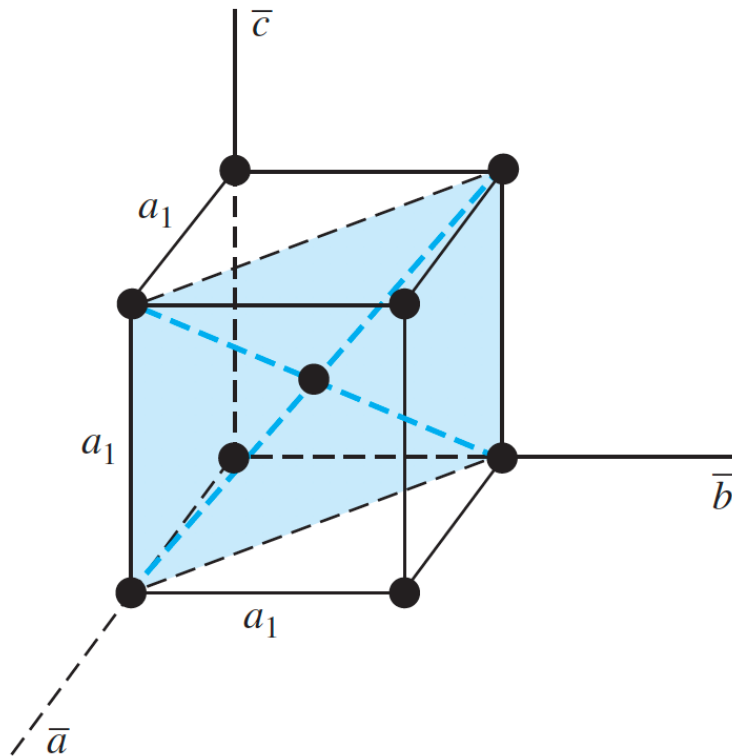
1.3 Space lattice

Crystalline Plane and Miller Index

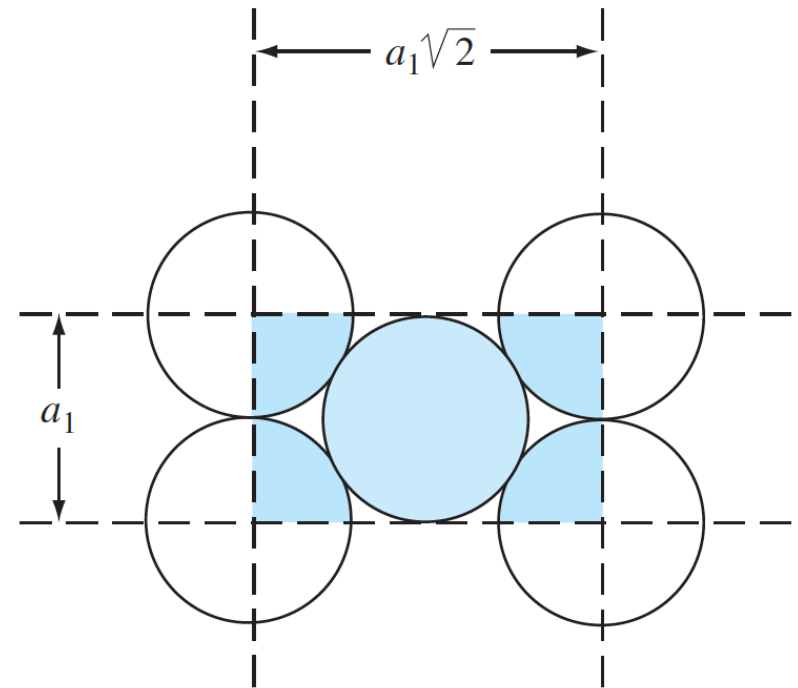


1.3 Space lattice

Crystalline Plane and Miller Index: surface density of atoms



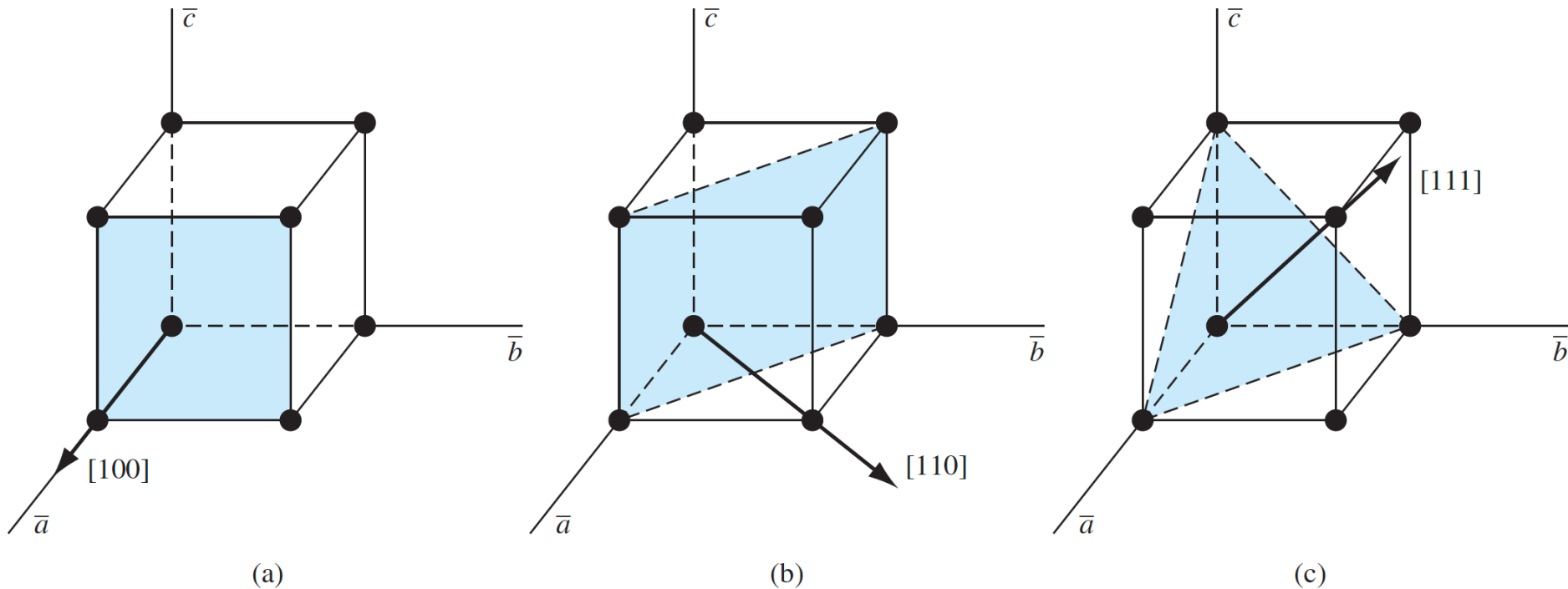
(a)



(b)

1.3 Space lattice

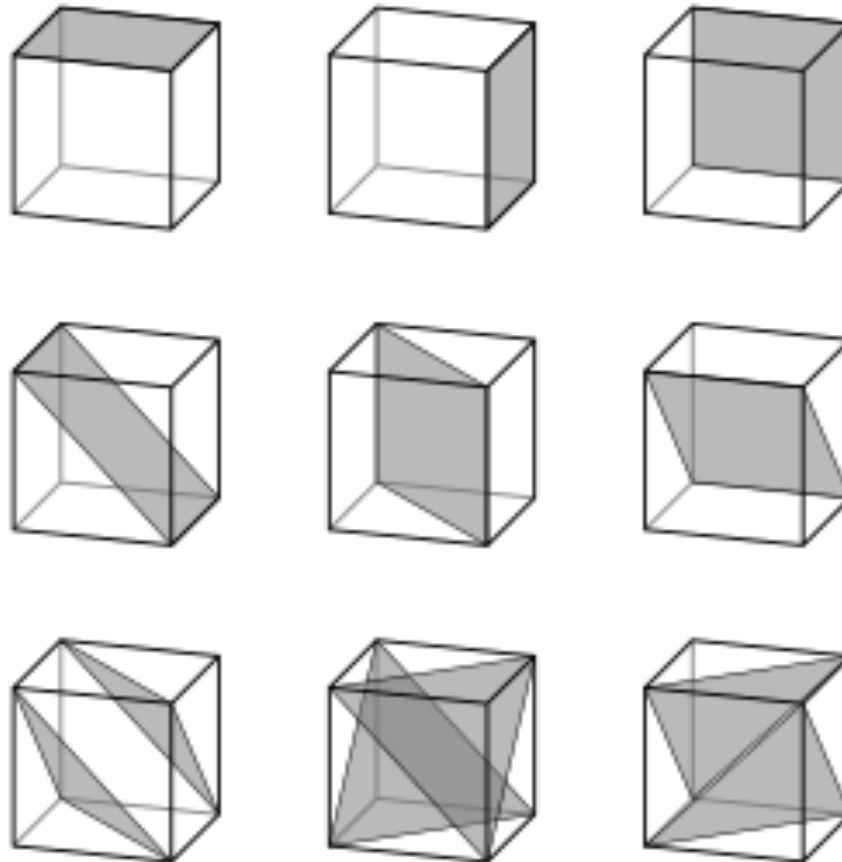
Directions in Crystals



In cubic lattice: $[hkl]$ direction is perpendicular to the (hkl) plane

Check your understanding

Identify crystalline plane



Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

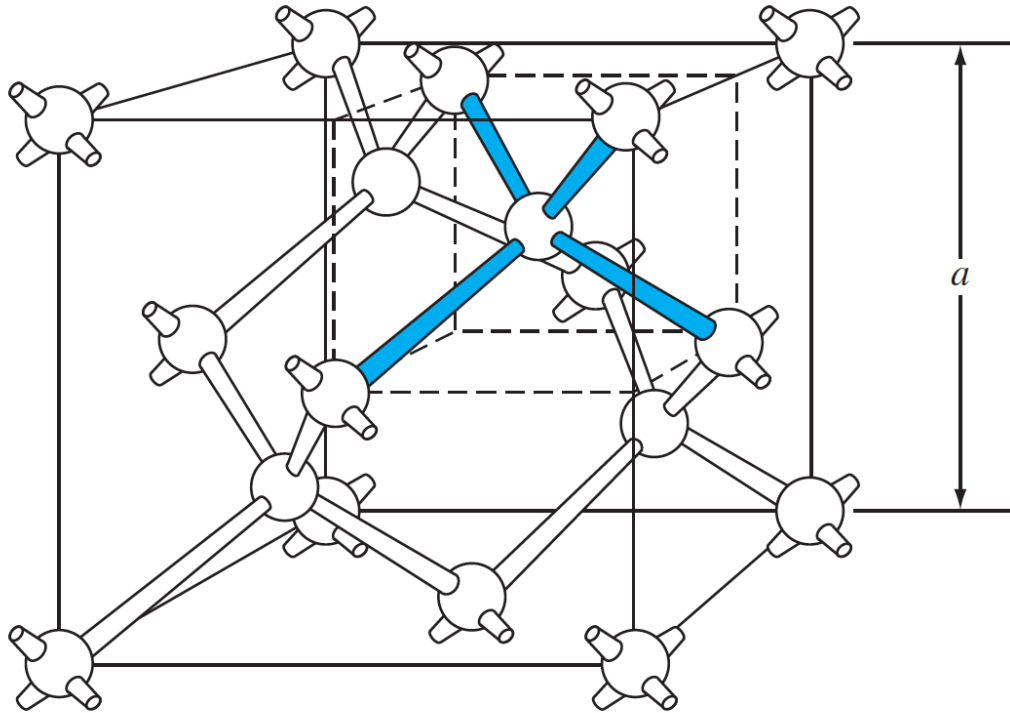
1.4 The diamond structure

1.5 Atomic bonding

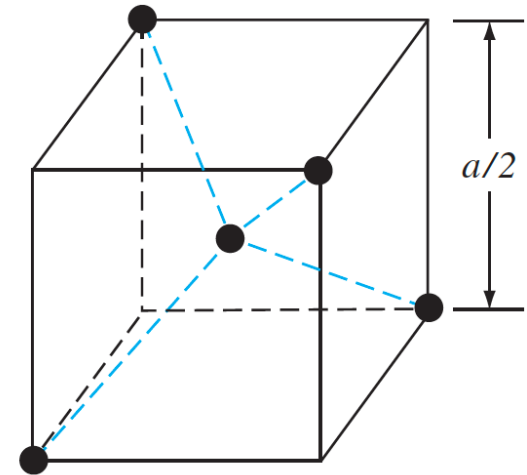
1.6 Imperfections and impurities in solids

1.4 The diamond structure

The diamond lattice



The diamond structure

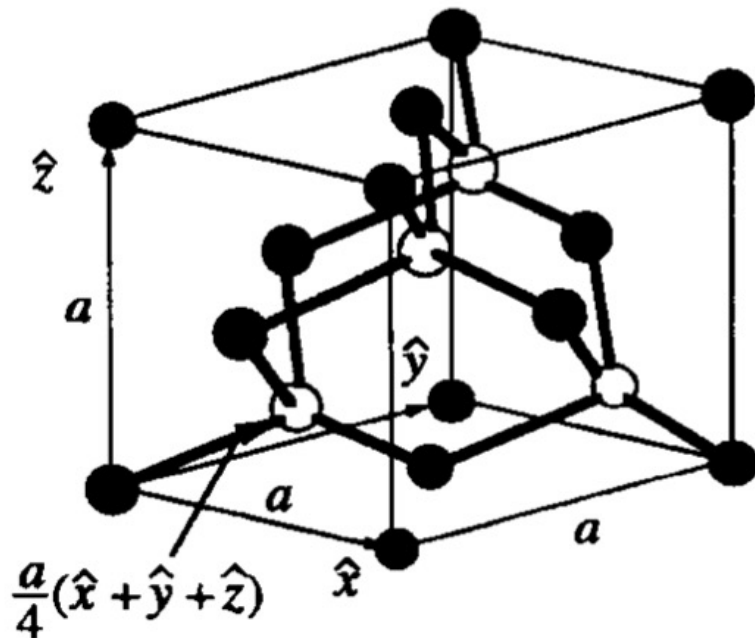


The tetrahedral structure of
closest neighbors in the diamond
lattice

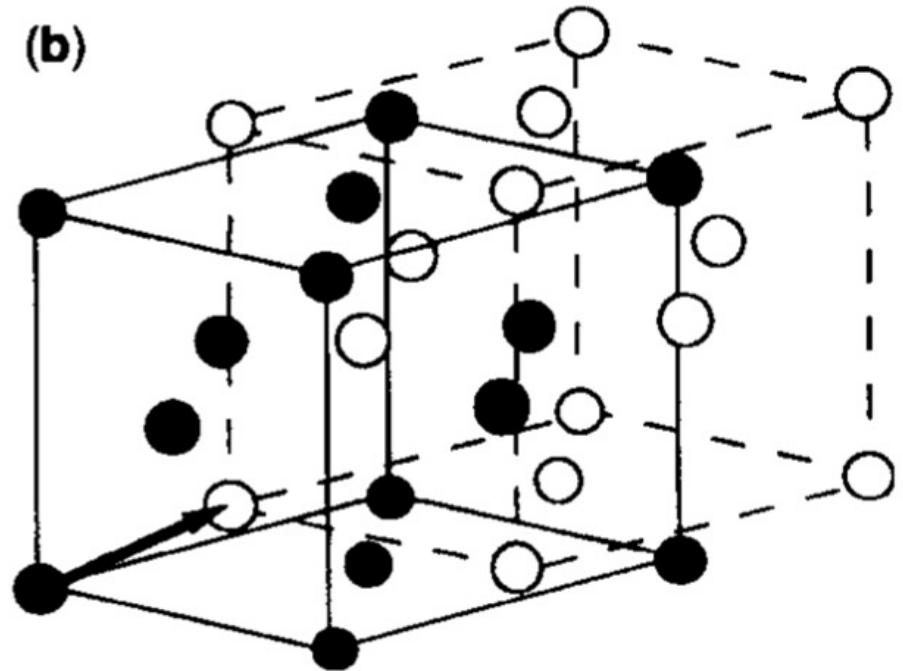
1.4 The diamond structure

The diamond lattice

(a)



(b)

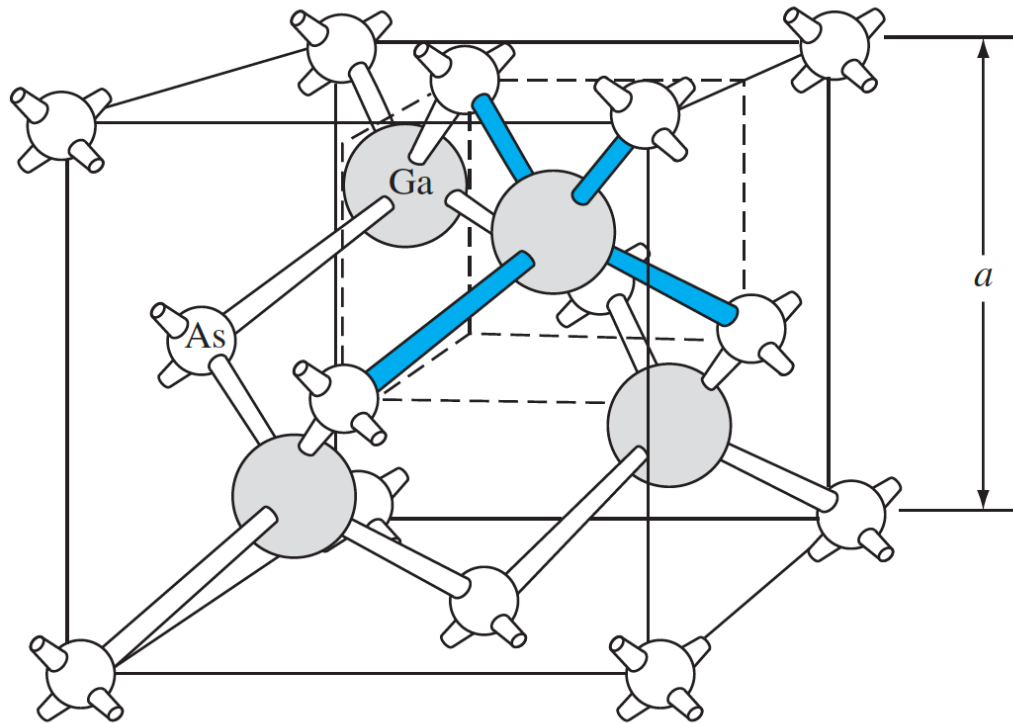


Equivalent to two face-centered cubics
sliding $\frac{1}{4}$ diagonal length along a diagonal

1.4 The diamond structure

The diamond lattice (all atoms are the same)

The zincblende lattice (two different types of atoms in diamond lattice)



Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

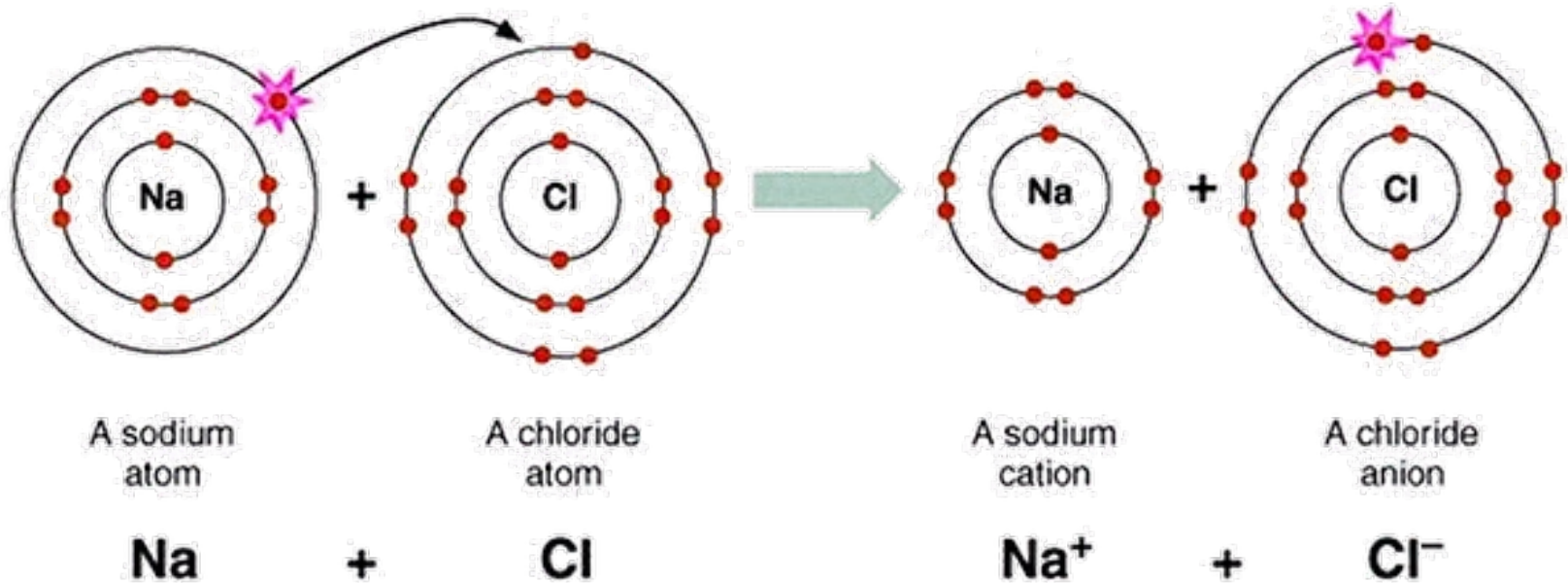
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.5 Chemical bonds

Chemical Bonds: Binding of atoms or ions

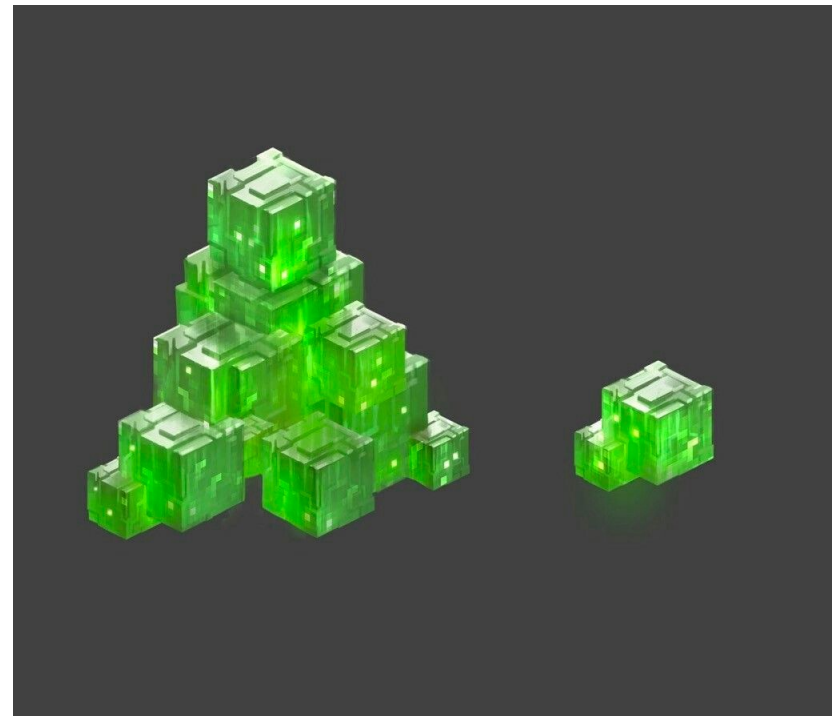
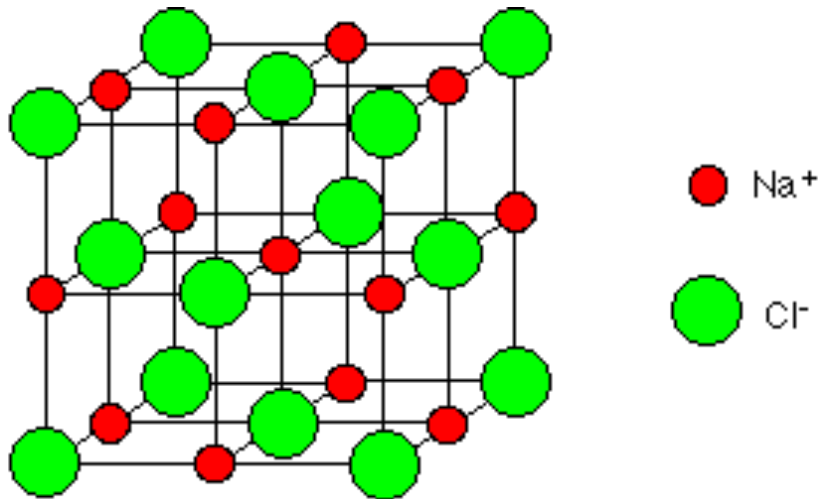
Ion bonds, metal bonds, covalent bonds



Ion bonds

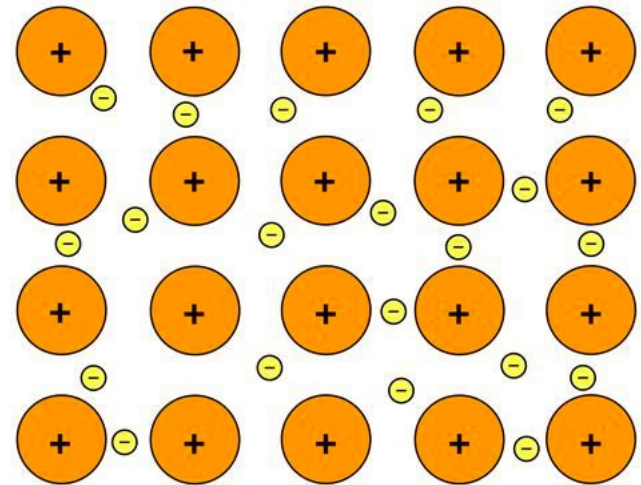
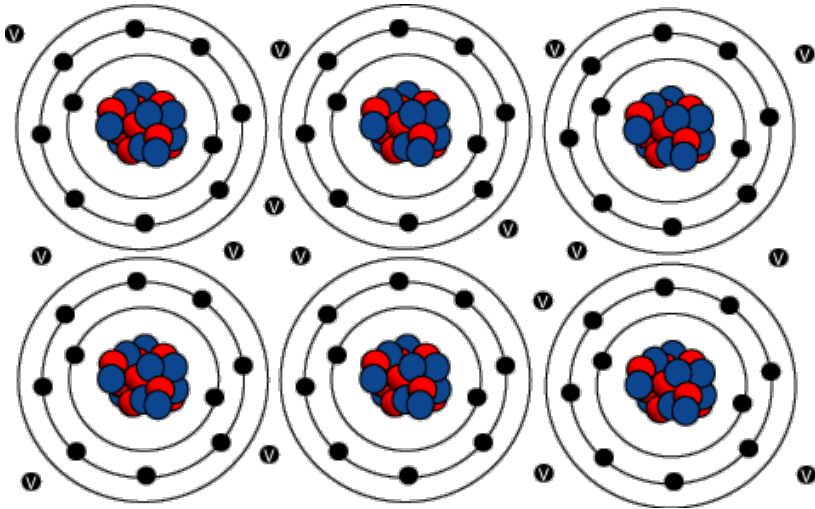
1.5 Chemical bonds

Ion Crystals



1.5 Chemical bonds

Metal bonds



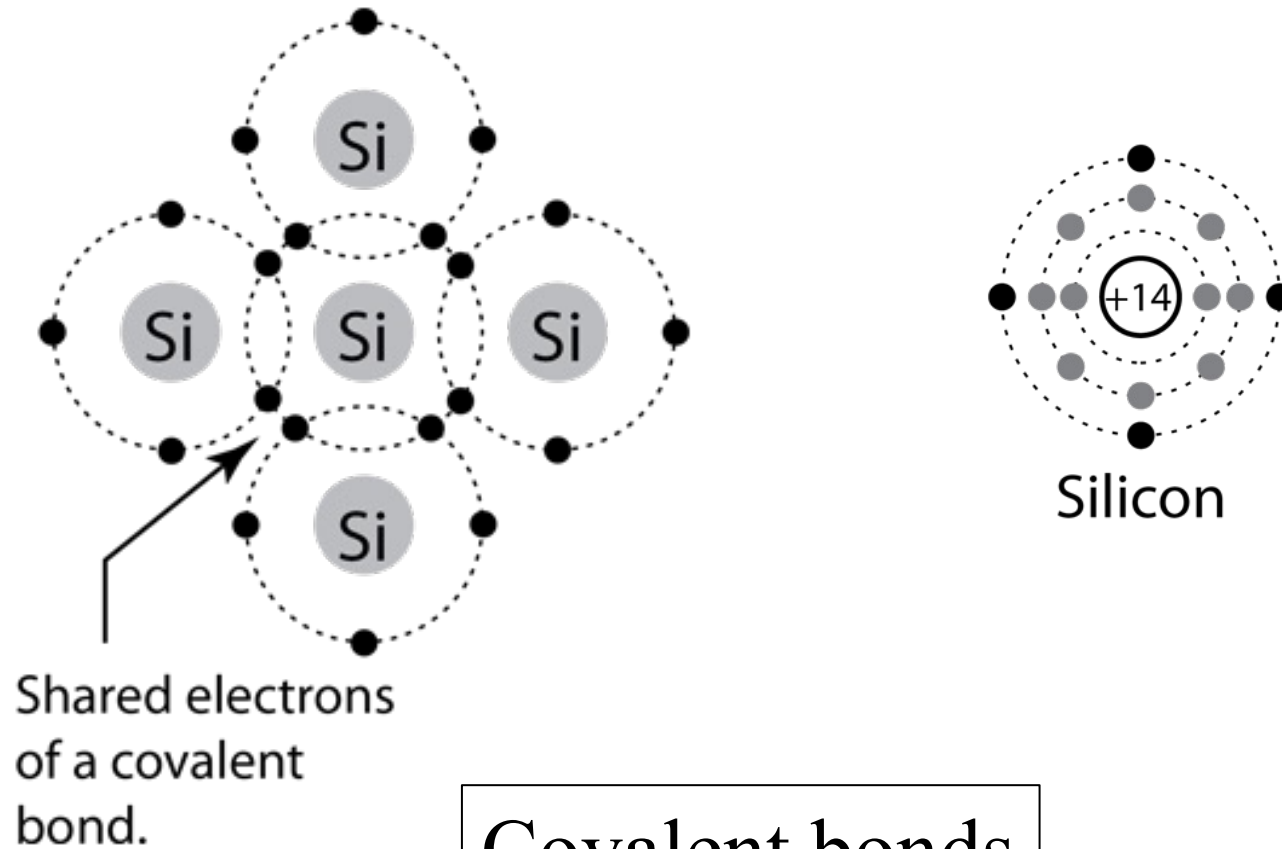
1.5 Chemical bonds

Metal Crystals



1.5 Chemical bonds

Covalent bonds: shared electrons in outer orbitals



1.5 Chemical bonds

Periodic Table of the Elements

1 H Hydrogen 1.008	2 He Helium 4.0026																			18 Ar Argon 39.948	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95598	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29	55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (284)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)	119 Uu Ununennium (295)	120 Uub Unbibium (296)	121 Uut Untrium (297)	122 Uuq Unquadrium (298)	123 Uub Unpentium (299)	124 Uuh Unhexium (300)	125 Uus Unseptium (301)	126 Uuq Unoctium (302)	127 Uuh Unnonium (303)	128 Uuo Unnilium (304)	129 Uuh Unnilennium (305)	130 Uub Unbihennium (306)	131 Uut Untrium (307)	132 Uuq Unquadrium (308)	133 Uub Unpentium (309)	134 Uuh Unhexium (310)	135 Uus Unseptium (311)	136 Uuo Unoctium (312)	137 Uuh Unnonium (313)	138 Uuo Unnilium (314)	139 Uuh Unnilennium (315)	140 Uub Unbihennium (316)	141 Uut Untrium (317)	142 Uuq Unquadrium (318)	143 Uub Unpentium (319)	144 Uuh Unhexium (320)	145 Uus Unseptium (321)	146 Uuo Unoctium (322)	147 Uuh Unnonium (323)	148 Uuo Unnilium (324)	149 Uuh Unnilennium (325)	150 Uub Unbihennium (326)	151 Uut Untrium (327)	152 Uuq Unquadrium (328)	153 Uub Unpentium (329)	154 Uuh Unhexium (330)	155 Uus Unseptium (331)	156 Uuo Unoctium (332)	157 Uuh Unnonium (333)	158 Uuo Unnilium (334)	159 Uuh Unnilennium (335)	160 Uub Unbihennium (336)	161 Uut Untrium (337)	162 Uuq Unquadrium (338)	163 Uub Unpentium (339)	164 Uuh Unhexium (340)	165 Uus Unseptium (341)	166 Uuo Unoctium (342)	167 Uuh Unnonium (343)	168 Uuo Unnilium (344)	169 Uuh Unnilennium (345)	170 Uub Unbihennium (346)	171 Uut Untrium (347)	172 Uuq Unquadrium (348)	173 Uub Unpentium (349)	174 Uuh Unhexium (350)	175 Uus Unseptium (351)	176 Uuo Unoctium (352)	177 Uuh Unnonium (353)	178 Uuo Unnilium (354)	179 Uuh Unnilennium (355)	180 Uub Unbihennium (356)	181 Uut Untrium (357)	182 Uuq Unquadrium (358)	183 Uub Unpentium (359)	184 Uuh Unhexium (360)	185 U
------------------------------------	------------------------------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	------------------------------------	--	--------------------------------------	---	---------------------------------------	---------------------------------------	--	---	-----------------------------------	-------------------------------------	-------------------------------------	-------------------------------------	----------------------------------	--------------------------------------	--	--------------------------------------	---------------------------------------	--------------------------------------	--------------------------------------	--	---------------------------------------	---------------------------------------	--	--	--	---------------------------------------	--	--------------------------------------	--	-------------------------------------	--------------------------------------	-------------------------------------	----------------------------------	---------------------------------------	--	------------------------------------	------------------------------------	---	--------------------------------------	----------------------	--------------------------------------	--	--------------------------------------	--------------------------------------	-------------------------------------	--------------------------------------	---------------------------------------	-----------------------------------	--------------------------------------	---------------------------------------	----------------------------------	--------------------------------------	--------------------------------------	--------------------------------------	-----------------------------------	--------------------------------------	------------------------------------	---------------------	--	--------------------------------------	---	--------------------------------------	--------------------------------------	---	---	--	--	---------------------------------------	--	--	--	---	--	---	--	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	---	--	--	--	---	---	---------------------------------------	--	---	--	-----------------

Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

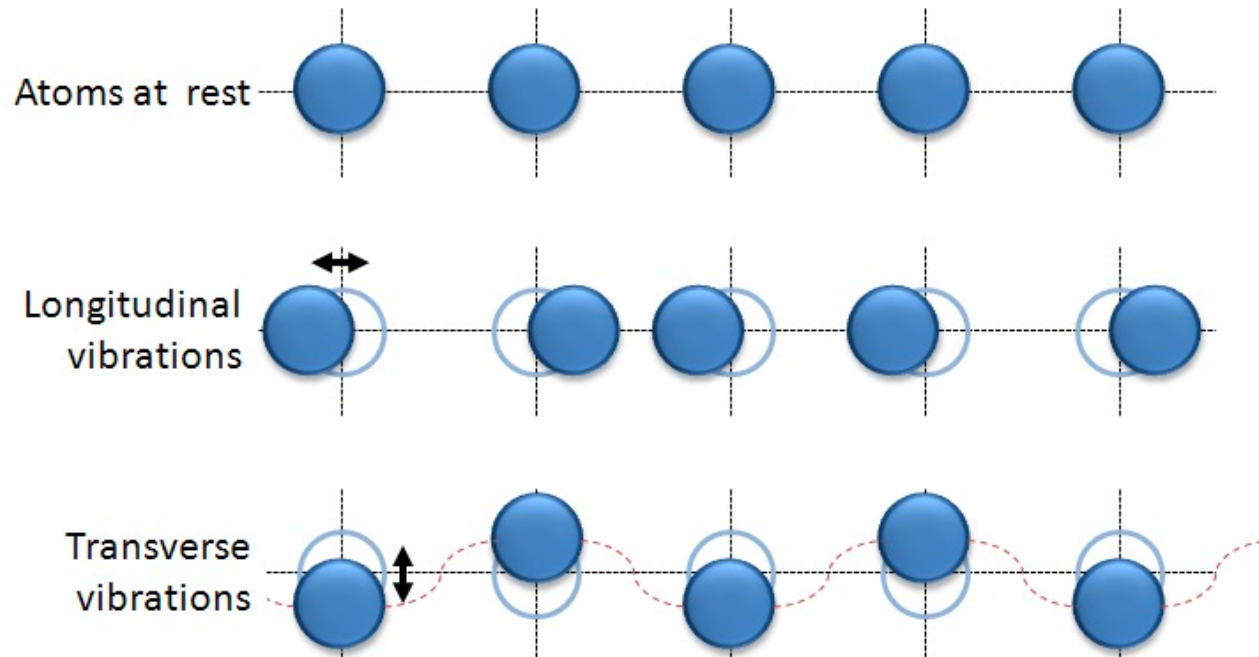
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations: thermal vibration or phonons

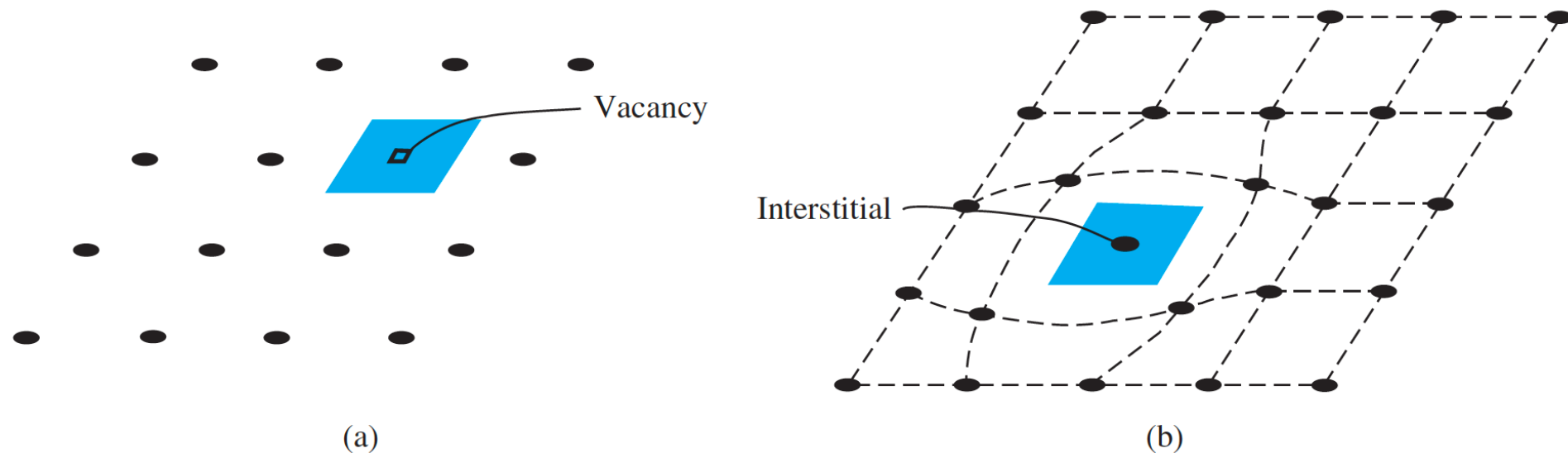


1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

Point defects: vacancies, interstitial defects, vacancy-interstitial defects



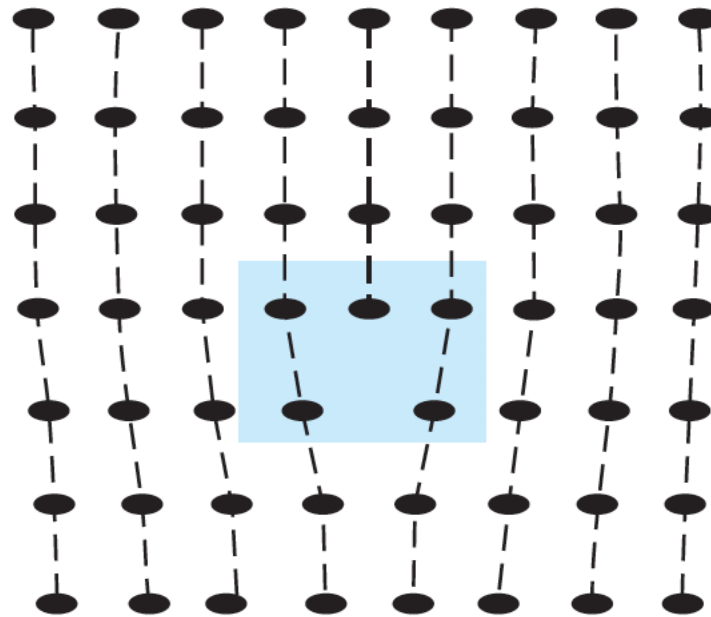
1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

Point defects: vacancies, interstitial defects, vacancy-interstitial defects

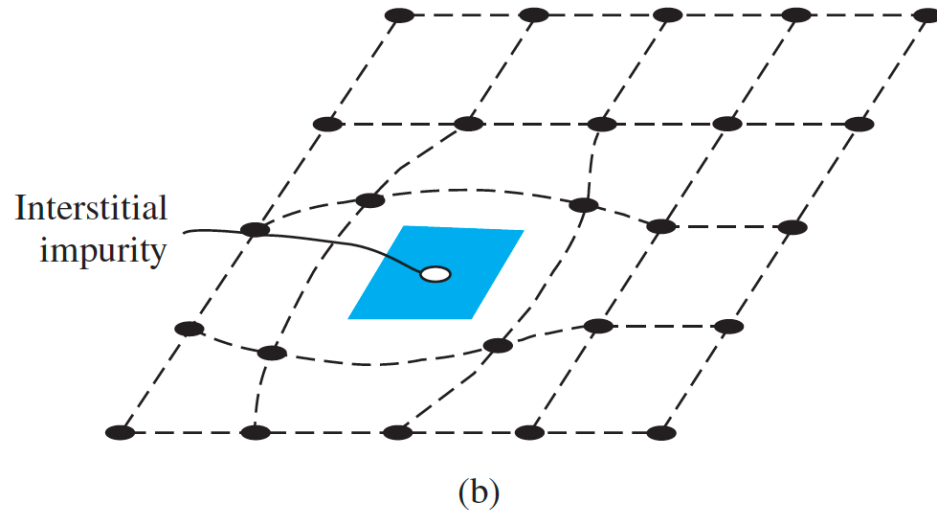
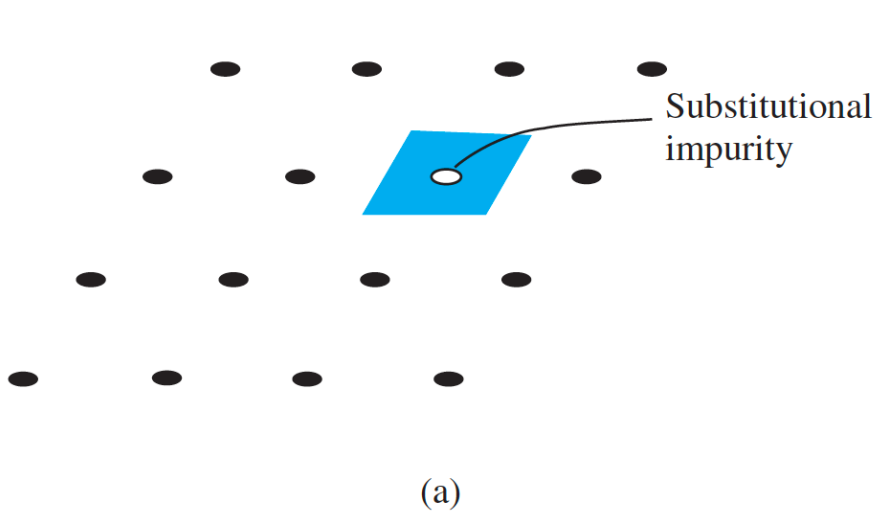
Line defects: line dislocation



Line dislocation

1.6 Imperfections and impurities in solids

Impurities in solids: foreign atoms



Dopants are special substitutional impurities.

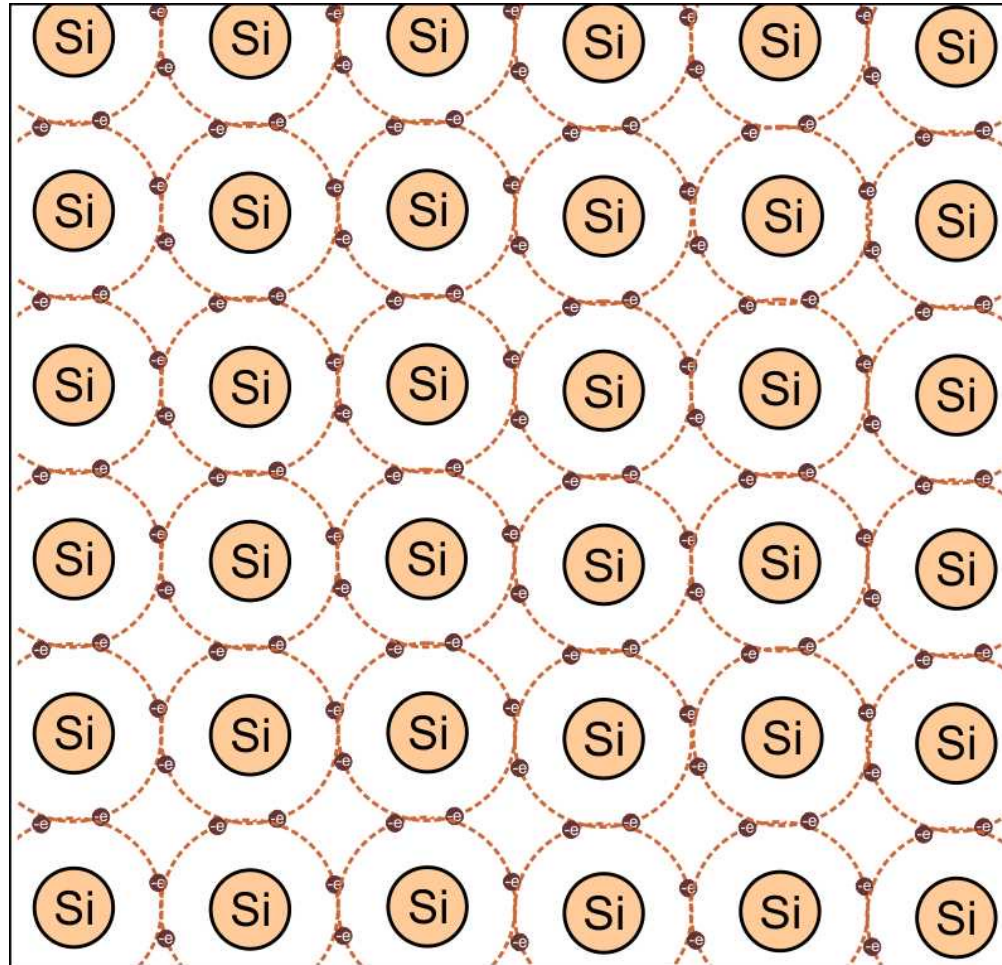
1.6 Imperfections and impurities in solids

Impurities in solids: foreign atoms

Periodic Table of the Elements

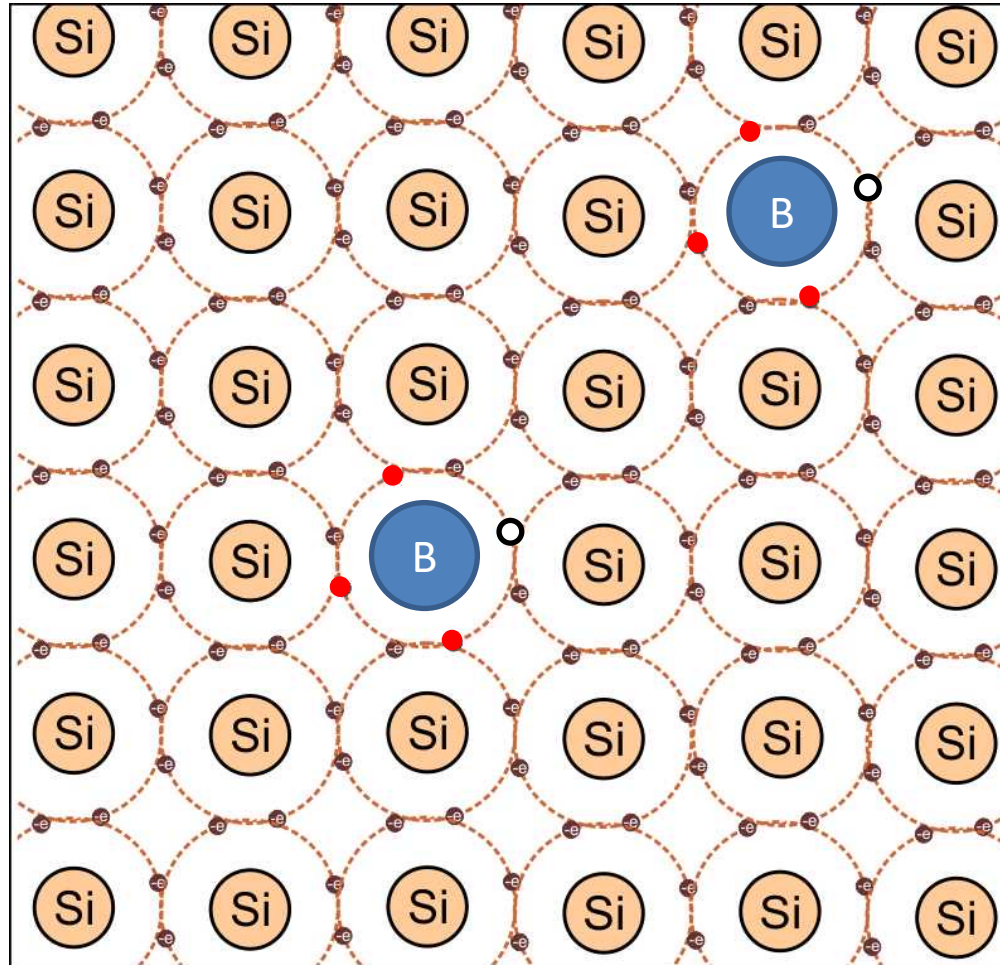
p-type																		n-type																		18	
																																				IIA	
																																				He	
																																				2	
																																				1	
																																				H	
																																				Hydrogen	
																																				1.008	
																																				1	
																																				IIA	
																																				3	
																																				Li	
																																				Lithium	
																																				6.94	
																																				2.0	
																																				4	
																																				Be	
																																				Beryllium	
																																				9.012	
																																				2.0	
																																				11	
																																				Na	
																																				Sodium	
																																				22.98976928	
																																				2.0	
																																				12	
																																				Mg	
																																				Magnesium	
																																				24.304	
																																				2.0	
																																				19	
																																				K	
																																				Potassium	
																																				39.0983	
																																				2.0	
																																				20	
																																				Ca	
																																				Calcium	
																																				40.078	
																																				2.0	
																																				37	
																																				Rb	
																																				Rubidium	
																																				85.4678	
																																				2.0	
																																				38	
																																				Sr	
																																				Strontium	
																																				87.62	
																																				2.0	
																																				55	
																																				Cs	
																																				Cesium	
																																				132.90545196	
																																				2.0	
																																				56	
																																				Ba	
																																				Barium	
																																				137.327	
																																				2.0	
																																				57-71	
																																				Lanthanides	
																																				72	
																																				Hf	
																																				Hafnium	
																																				178.49	
																																				2.0	
																																				73	
																																				Ta	
																																				Tantalum	
																																				180.94788	
																																				2.0	
																																				104	
																																				Rf	
																																				Rutherfordium	
																																				(261)	
																																				2.0	
																																				105	
																																				Db	
																																				Dubnium	
																																				(268)	
																																				2.0	
																																				106	
																																				Sg	
																																				Seaborgium	
																																				(266)	
																																				2.0	
																																				107	
																																				Bh	
																																				Bohrium	
																																				(277)	
																																				2.0	
																																				108	
																																				Hs	
																																				Hassium	
																																				(277)	
																																				2.0	
																																				109	
																																				Mt	
																																				Meitnerium	
																																				(276)	
																																				2.0	
																																				110	
																																				Ds	
																																				Darmstadtium	
																																				(281)	
																																				2.0	
																																				111	
																																				Rg	
																																				Roentgenium	
																																				(282)	
																																				2.0	
																																				112	
																																				Cn	
																																				Copernicium	
																																				(285)	
																																				2.0	
																																				113	
																																				Nh	
																																				Nihonium	
																																				(284)	
																																				2.0	
																																				114	
																																				Fl	
																																				Flerovium	
																																				(289)	
																																				2.0	
																																				115	
																																				Mc	
																																				Moscovium	
																																				(290)	
																																				2.0	
																																				116	
																																				Lv	
																																				Livermorium	
																																				(293)	
																																				2.0	
																																				117	
																																				Ts	
																																				Tennessine	
																																				(294)	
																																				2.0	
																																				118	
																																				Og	
																																				Oganesson	
																																				(294)	
																																				2.0	
																																				57	
																																				La	
																																				Lanthanum	
																																				138.91	
																																				2.0	
																																				58	
																																				Ce	
																																				Cerium	
																																				140.12	
																																				2.0	
																																				59	
																																				Pr	
																																				Praseodymium	
																																				140.91	
																																				2.0	
																																				60	
																																				Nd	
																																				Neodymium	
																																				144.24	
																																				2.0	
																																				61	
																																				Pm	
																																				Promethium	
																																				(145)	
																																				2.0	
																																				62	
																																				Sm	
																																				Samarium	
																																				150.36	
																																				2.0	
																																				63	
																																				Eu	
																																				Europium	
																																				151.96	
																																				2.0	
																																				64	
																																				Gd	
																																				Gadolinium	
																																				157.25	
																																				2.0	
																																				65	
																																				Tb	
																																				Terbium	
																																				158.93	
																																				2.0	
																																				66	
																																				Dy	
																																				Dysprosium	
																																				162.50	
																																				2.0	
																																				67	
																																				Ho	
																																				Holmium	
																																				164.93	
																																				2.0	
																																				68	
																																				Er	
																																				Erbium	
																																				167.26	
																																				2.0	
																																				69	
																																				Tm	
																																				Thulium	
																																				168.93	
																																				2.0	
																																				70	
																																				Yb	
																																				Ytterbium	
																																				173.05	
																																				2.0	
																																				71	
																																				Lu	
																																				Lutetium	
																																				174.967	
																																				2.0	
																																				89	
																																				Ac	
																																				Actinium	
																																				(227)	
																																				2.0	
																																				90	
																																				Th	
																																				Thorium	
																																				232.04	
																																				2.0	
																																				91	
																																				Pa	
																																				Protactinium	
																																				231.04	
																																				2.0	
																																				92	
																																				U	
																																				Uranium	
																																				238.03	
																																				2.0	
																																				93	
																																				Np	
																																				Neptunium	
																																				(237)	
																																				2.0	
																																				94	
																																				Pu	
																																				Plutonium	
																																				(244)	
																																				2.0	
																																				95	
																																				Am	
																																				Americium	
																																				(243)	
																																				2.0	
																																				96	
																																				Cm	
																																				Curium	
																																				(247)	
																																				2.0	
																																				97	
																																				Bk	
																																				Berkelium	
																																				(247)	
																																				2.0	
																																				98	
																																				Cf	
																																				Californium	
																																				(251)	
																																				2.0	
																																				99	
																																				Es	
																																				Einsteinium	
																																				(252)	
																																				2.0	
																																				100	
																																				Fm	
																																				Fermium	
																																				(257)	
																																				2.0	
																																				101	
																																				Md	
																																				Mendelevium	
																																				(258)	
																																				2.0	
																																				102	
																																				No	
																																				Nobelium	
																																				(259)	
																																				2.0	
																																				103	
																																				Lr	
																																				Lawrencium	
																																				(260)	
																																				2.0	

1.6 Imperfections and impurities in solids



1.6 Imperfections and impurities in solids

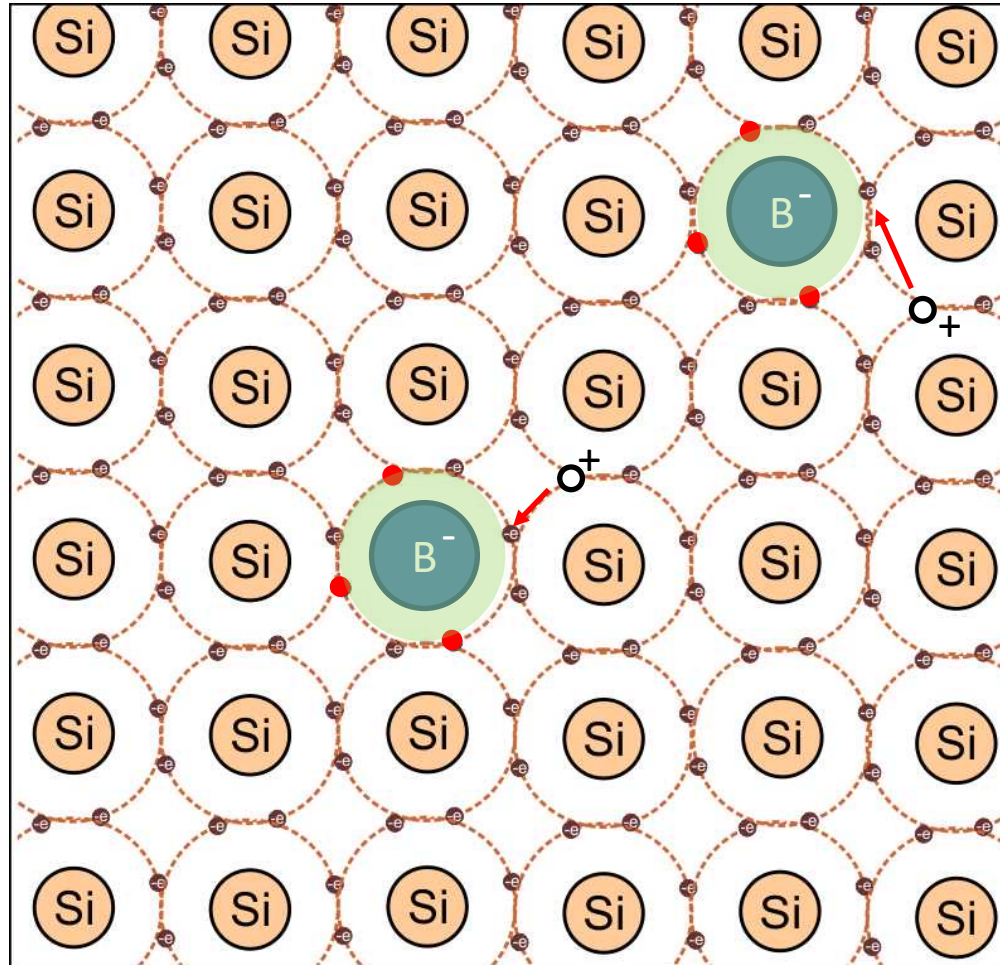
p-type
doping



Acceptor-type of doping

1.6 Imperfections and impurities in solids

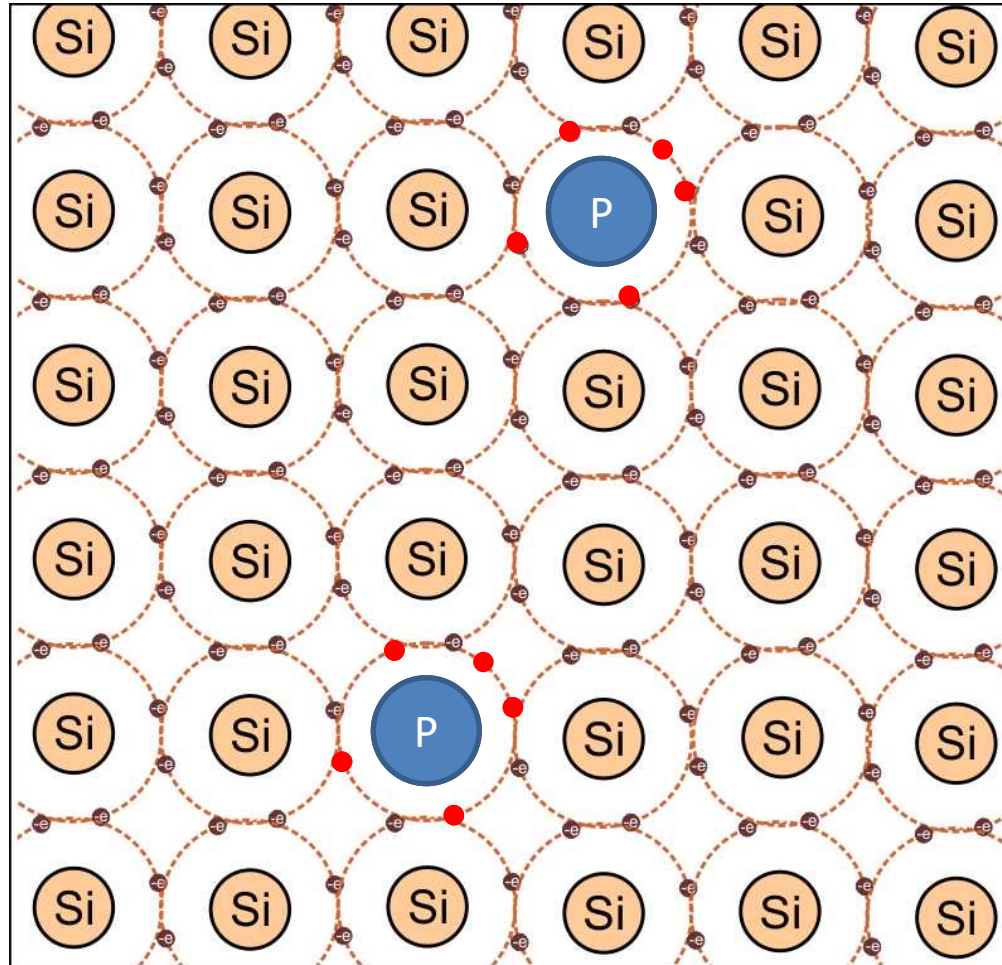
p-type
doping



Acceptor-type of doping

1.6 Imperfections and impurities in solids

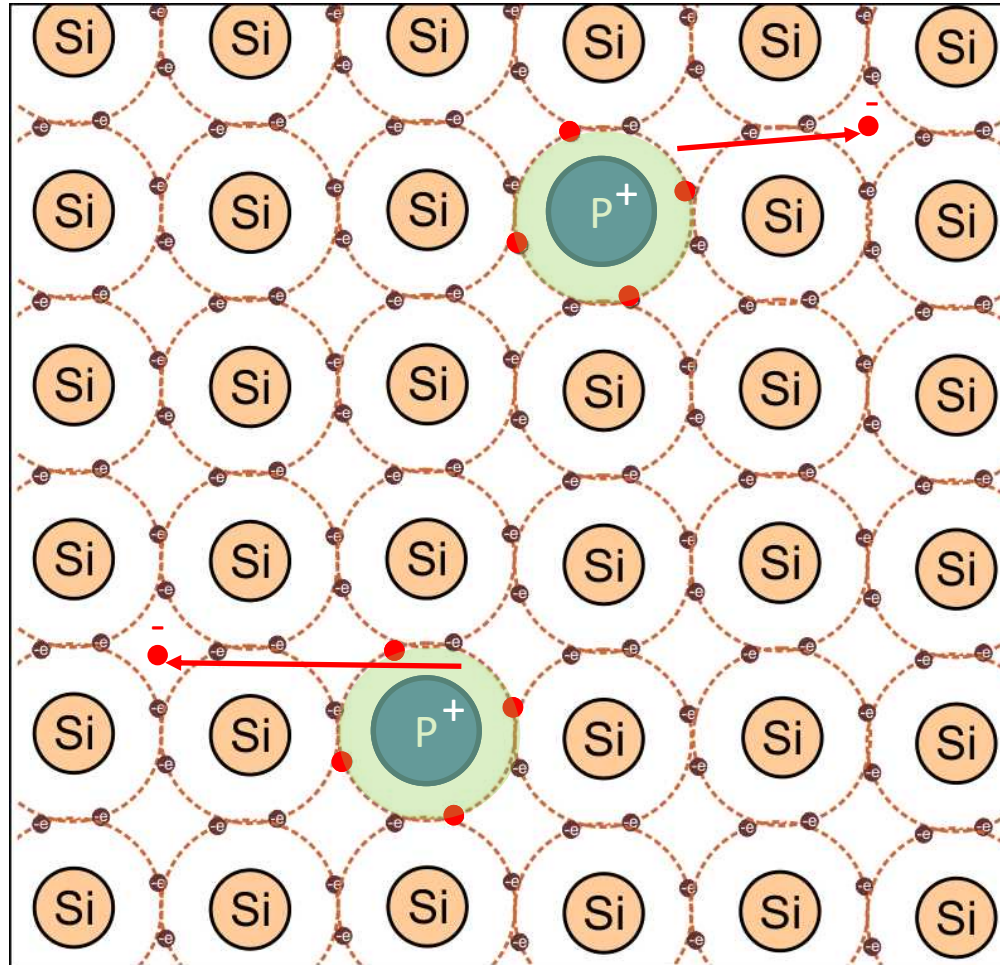
n-type
doping



Donor-type of doping

1.6 Imperfections and impurities in solids

n-type
doping



Donor-type of doping

Check your understanding

- For Ga, Sn, As, Sb in Si, which forms n-type or p-type doping?
- Will Ge in Si form n-type or p-type doping?

Periodic Table of the Elements

IA																		VIIIA																	
1 H Hydrogen 1.008																		2 He Helium 4.0026																	
3 Li Lithium 6.94		4 Be Beryllium 9.012														10 Ne Neon 20.180																			
11 Na Sodium 22.98976928		12 Mg Magnesium 24.304														18 Ar Argon 39.948																			
19 K Potassium 39.0983		20 Ca Calcium 40.078														36 Kr Krypton 83.798																			
37 Rb Rubidium 85.4678		38 Sr Strontium 87.62														54 Xe Xenon 131.29																			
55 Cs Cesium 132.90545196		56 Ba Barium 137.327														86 Rn Radon 222																			
87 Fr Francium 223		88 Ra Radium 226														118 Og Oganesson 294																			
IIA																		VIIA																	
5 B Boron 10.81		6 C Carbon 12.011		7 N Nitrogen 14.007		8 O Oxygen 15.999		9 F Fluorine 18.998		10 Ne Neon 20.180																									
13 Al Aluminum 26.982		14 Si Silicon 28.085		15 P Phosphorus 30.974		16 S Sulfur 32.06		17 Cl Chlorine 35.45		18 Ar Argon 39.948																									
31 Ga Gallium 69.723		32 Ge Germanium 72.630		33 As Arsenic 74.921		34 Se Selenium 78.971		35 Br Bromine 79.904		36 Kr Krypton 83.798																									
49 In Indium 114.82		50 Sn Tin 118.71		51 Sb Antimony 121.757		52 Te Tellurium 127.60		53 I Iodine 126.905		54 Xe Xenon 131.29																									
81 Tl Thallium 204.38		82 Pb Lead 207.2		83 Bi Bismuth 208.98		84 Po Polonium 209		85 At Astatine 210		86 Rn Radon 222																									
113 Nh Nihonium 284		114 Fl Flerovium 289		115 Mc Moscovium 290		116 Lv Livermorium 293		117 Ts Tennessine 294		118 Og Oganesson 294																									
State of matter (color of name) GAS LIQUID SOLID UNKNOWN																		Subcategory in the metal-metalloid-nonmetal trend (color of background) Alkali metals Lanthanides Metalloids Unknown chemical properties Alkaline earth metals Actinides Reactive nonmetals Transition metals Post-transition metals Noble gases																	
21 Sc Scandium 44.955908		22 Ti Titanium 47.867		23 V Vanadium 50.9415		24 Cr Chromium 51.9961		25 Mn Manganese 54.938044		26 Fe Iron 55.845		27 Co Cobalt 58.933		28 Ni Nickel 58.693		29 Cu Copper 63.546		30 Zn Zinc 65.38		31 Ga Gallium 69.723		32 Ge Germanium 72.630		33 As Arsenic 74.921		34 Se Selenium 78.971		35 Br Bromine 79.904		36 Kr Krypton 83.798					
39 Y Yttrium 88.90584		40 Zr Zirconium 91.224		41 Nb Niobium 92.90637		42 Mo Molybdenum 95.94		43 Tc Technetium 98		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.91		46 Pd Palladium 106.42		47 Ag Silver 107.87		48 Cd Cadmium 112.41		49 In Indium 114.82		50 Sn Tin 118.71		51 Sb Antimony 121.757		52 Te Tellurium 127.60		53 I Iodine 126.905		54 Xe Xenon 131.29					
57-71 Lanthanides		72 Hf Hafnium 178.49		73 Ta Tantalum 180.94788		74 W Tungsten 183.84		75 Re Rhenium 186.21		76 Os Osmium 190.23		77 Ir Iridium 192.22		78 Pt Platinum 195.08		79 Au Gold 196.967		80 Hg Mercury 200.59		81 Tl Thallium 204.38		82 Pb Lead 207.2		83 Bi Bismuth 208.98		84 Po Polonium 209		85 At Astatine 210		86 Rn Radon 222					
89-103 Actinides		104 Rf Rutherfordium 261		105 Db Dubnium 268		106 Sg Seaborgium 269		107 Bh Bohrium 270		108 Hs Hassium 277		109 Mt Meitnerium 276		110 Ds Darmstadtium 281		111 Rg Roentgenium 282		112 Cn Copernicium 285		113 Nh Nihonium 284		114 Fl Flerovium 289		115 Mc Moscovium 290		116 Lv Livermorium 293		117 Ts Tennessine 294		118 Og Oganesson 294					
57 La Lanthanum 138.905		58 Ce Cerium 140.12		59 Pr Praseodymium 140.90765		60 Nd Neodymium 144.24		61 Pm Promethium 145		62 Sm Samarium 150.36		63 Eu Europium 151.964		64 Gd Gadolinium 157.25		65 Tb Terbium 158.925		66 Dy Dysprosium 162.50		67 Ho Holmium 164.93032		68 Er Erbium 167.259		69 Tm Thulium 168.934		70 Yb Ytterbium 173.054		71 Lu Lutetium 174.967							
89 Ac Actinium 227		90 Th Thorium 232.04		91 Pa Protactinium 231.04		92 U Uranium 238.03		93 Np Neptunium 237		94 Pu Plutonium 244		95 Am Americium 243		96 Cm Curium 247		97 Bk Berkelium 247		98 Cf Californium 251		99 Es Einsteinium 252		100 Fm Fermium 257		101 Md Mendelevium 258		102 No Nobelium 259		103 Lr Lawrencium 262							