
VE320 – Summer 2022

Introduction to Semiconductor Devices

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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

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all sems

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

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

Electrons per shell

Atomic Number →

Name →

Symbol →

Atomic Weight →

Atoms per shell →

Unknown chemical properties

1 IA	1 H Hydrogen 1.008 1	2 IIA	3 Li Lithium 6.94 2-1	4 Be Beryllium 9.012 2-2	5 VIB	6 VIIIB	7 VIIIIB	8 VIIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
													12 B Boron 10.81 2-3	6 C Carbon 12.011 2-4	7 N Nitrogen 14.007 2-5	8 O Oxygen 15.999 2-6	9 F Fluorine 18.998 2-7	10 Ne Neon 20.180 2-8
3 IIIB	4 IVB	5 VB	6 VIIB	7 VIIIB	8 VIIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA			
19	20 Ca Calcium 40.078 2-8-2	21 Sc Scandium 47.867 2-8-1-2	22 Ti Titanium 47.867 2-8-2	23 V Vanadium 50.945 2-8-1-2	24 Cr Chromium 51.9961 2-8-1-2	25 Mn Manganese 54.938044 2-8-2	26 Fe Iron 55.845 2-8-2	27 Co Cobalt 58.933 2-8-2	28 Ni Nickel 58.693 2-8-1-2	29 Cu Copper 63.546 2-8-1	30 Zn Zinc 69.38 2-8-2	31 Ga Gallium 69.723 2-8-3	32 Ge Germanium 72.630 2-8-4	33 As Arsenic 74.922 2-8-5	34 Se Selenium 78.971 2-8-6	35 Br Bromine 79.904 2-8-7	36 Kr Krypton 83.798 2-8-8	
37 Rb Rubidium 35.45 2-8-8-1	38 Sr Strontium 88.0584 2-8-8-2	39 Y Yttrium 88.9054 2-8-8-2	40 Zr Zirconium 91.224 2-8-8-2	41 Nb Niobium 92.9063 2-8-8-2	42 Mo Molybdenum 95.97 2-8-8-2	43 Tc Technetium 97.90 2-8-8-2	44 Ru Ruthenium 101.07 2-8-8-2	45 Rh Rhodium 102.91 2-8-8-2	46 Pd Palladium 106.42 2-8-8-2	47 Ag Silver 107.87 2-8-8-2	48 Cd Cadmium 110.41 2-8-8-2	49 In Indium 114.82 2-8-8-3	50 Sn Tin 118.71 2-8-8-3	51 Sb Antimony 121.77 2-8-8-3	52 Te Tellurium 127.60 2-8-8-4	53 I Iodine 126.90 2-8-8-4	54 Xe Xenon 131.33 2-8-8-8	
55 Cs Cesium 132.90545196 2-8-18-8-1	56 Ba Barium 137.327 2-8-18-8-2	57-71 Lanthanides	72 Hf Hafnium 178.49 2-8-8-10-2	73 Ta Tantalum 180.94788 2-8-8-10-2	74 W Tungsten 183.84 2-8-8-10-2	75 Re Rhenium 184.21 2-8-8-10-2	76 Os Osmium 190.23 2-8-8-10-2	77 Ir Iridium 192.22 2-8-8-10-2	78 Pt Platinum 195.08 2-8-8-10-2	79 Au Gold 196.97 2-8-8-10-2	80 Hg Mercury 200.59 2-8-8-10-2	81 Tl Thallium 204.38 2-8-8-10-2	82 Pb Lead 207.2 2-8-8-10-2	83 Bi Bismuth 208.98 2-8-8-10-2	84 Po Polonium (209) 2-8-18-32-18-6	85 At Astatine (210) 2-8-18-32-18-7	86 Rn Radon (222) 2-8-18-32-18-8	
87 Fr Francium (223) 2-8-18-32-18-2	88 Ra Radium (226) 2-8-18-32-18-2	89-103 Actinides	104 Rf Rutherfordium (267) 2-8-18-32-32-2	105 Db Dubnium (268) 2-8-18-32-32-2	106 Sg Seaborgium (269) 2-8-18-32-32-2	107 Bh Bohrium (270) 2-8-18-32-32-2	108 Hs Hassium (271) 2-8-18-32-32-2	109 Mt Meitnerium (278) 2-8-18-32-32-2	110 Ds Darmstadtium (280) 2-8-18-32-32-2	111 Rg Roentgenium (282) 2-8-18-32-32-2	112 Cn Copernicium (285) 2-8-18-32-32-2	113 Nh Nihonium (286) 2-8-18-32-32-2	114 Fl Flerovium (289) 2-8-18-32-32-2	115 Mc Moscovium (290) 2-8-18-32-32-2	116 Lv Livermorium (293) 2-8-18-32-32-2	117 Ts Tennessine (294) 2-8-18-32-32-2	118 Og Oganesson (298) 2-8-18-32-32-2	
57 La Lanthanum 138.91 2-8-8-18-2	58 Ce Cerium 140.12 2-8-8-18-2	59 Pr Praseodymium 140.91 2-8-8-18-2	60 Nd Neodymium 144.26 2-8-8-18-2	61 Pm Promethium (145) 2-8-8-18-2	62 Sm Samarium 150.36 2-8-8-18-2	63 Eu Europium 151.96 2-8-8-18-2	64 Gd Gadolinium 157.26 2-8-8-18-2	65 Tb Terbium 158.93 2-8-8-18-2	66 Dy Dysprosium 162.50 2-8-8-18-2	67 Ho Holmium 164.93 2-8-8-18-2	68 Er Erbium 167.26 2-8-8-18-2	69 Tm Thulium 168.93 2-8-8-18-2	70 Yb Ytterbium 173.05 2-8-8-18-2	71 Lu Lutetium 174.97 2-8-8-18-2				
89 Ac Actinium (227) 2-8-18-32-18-2	90 Th Thorium 232.04 2-8-18-32-18-2	91 Pa Protactinium 231.04 2-8-18-32-18-2	92 U Uranium 238.03 2-8-18-32-18-2	93 Np Neptunium (237) 2-8-18-32-26-2	94 Pu Plutonium (244) 2-8-18-32-26-2	95 Am Americium (243) 2-8-18-32-26-2	96 Cm Curium (247) 2-8-18-32-26-2	97 Bk Berkelium (247) 2-8-18-32-26-2	98 Cf Californium (251) 2-8-18-32-26-2	99 Einsteinium (253) 2-8-18-32-26-2	100 Es Fermium (257) 2-8-18-32-26-2	101 Md Mendelevium (258) 2-8-18-32-26-2	102 No Nobelium (259) 2-8-18-32-26-2	103 Lr Lawrencium (264) 2-8-18-32-26-2				

1.1 Semiconductor materials

Table 1.1 | A portion of the periodic table

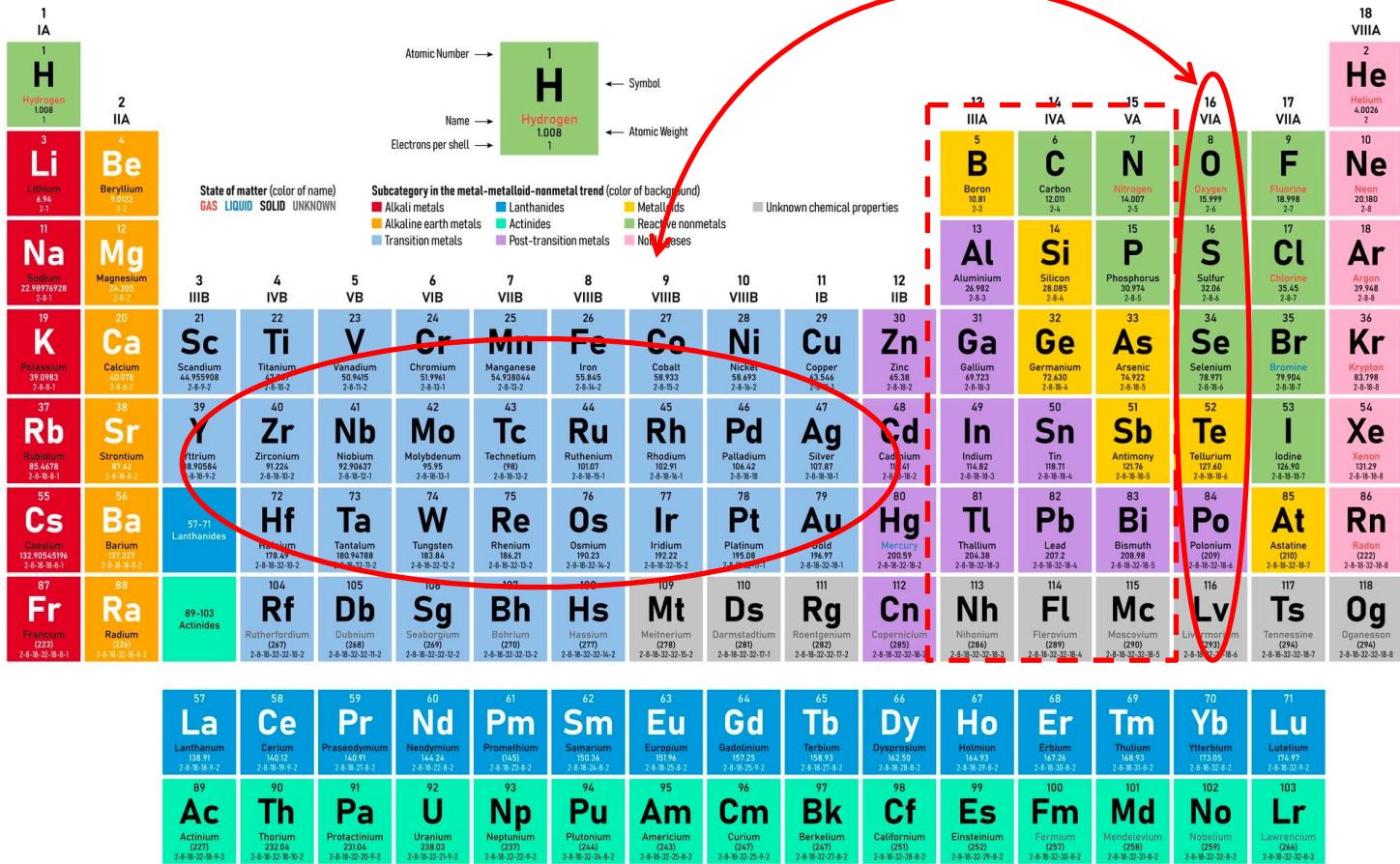
III	IV	V
5 B Boron	6 C Carbon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic
49 In Indium		51 Sb Antimony

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



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

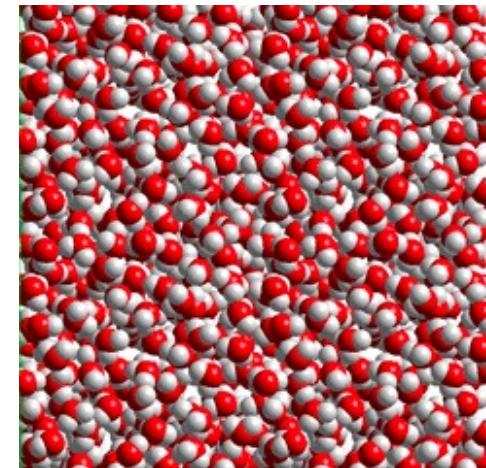
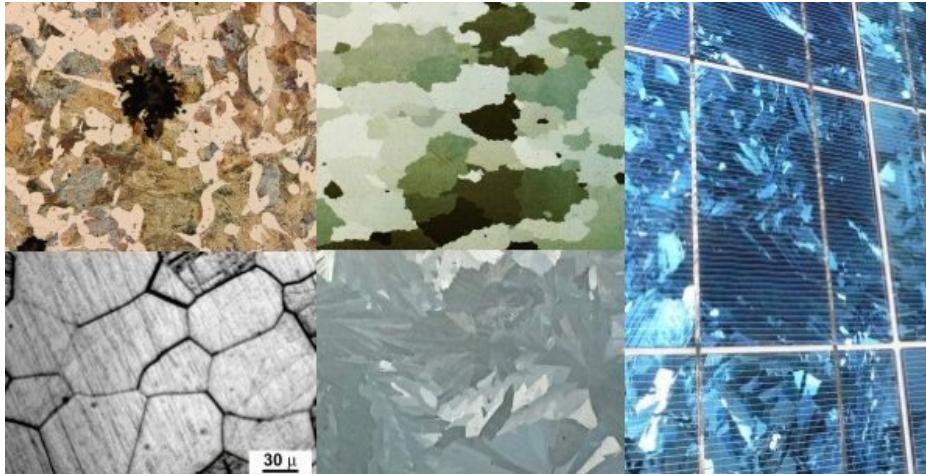
1.6 Imperfections and impurities in solids



1.2 Type of Solids

Solids:

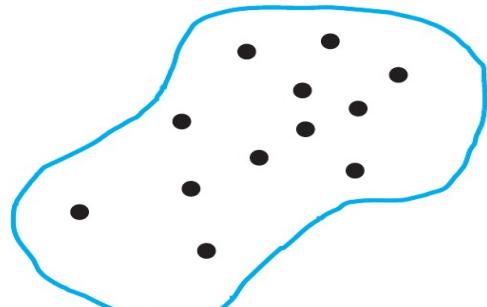
- Single crystals
- Polycrystals
- Amorphous



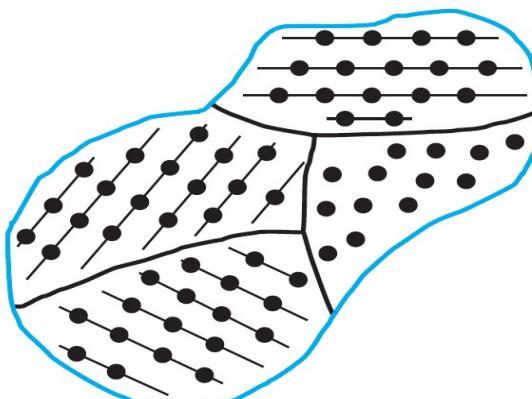
1.2 Type of Solids

Solids :

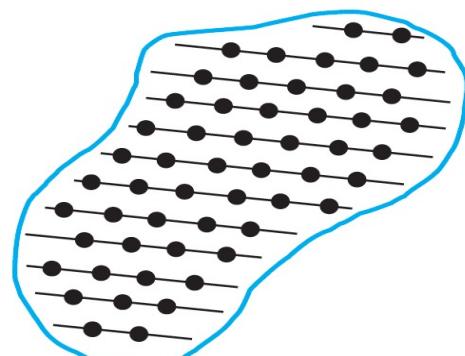
- Amorphous
- Polycrystals
- Single crystals



(a)



(b)



(c)

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

Multiple crystalline grains randomly packed

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

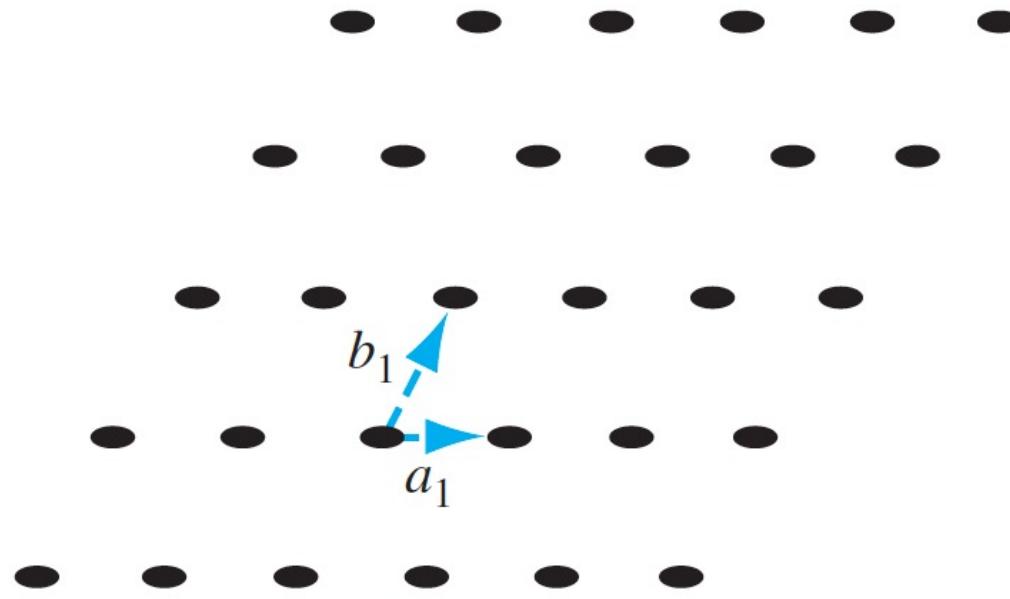
1.5 Atomic bonding

1.6 Imperfections and impurities in solids



1.3 Space lattice

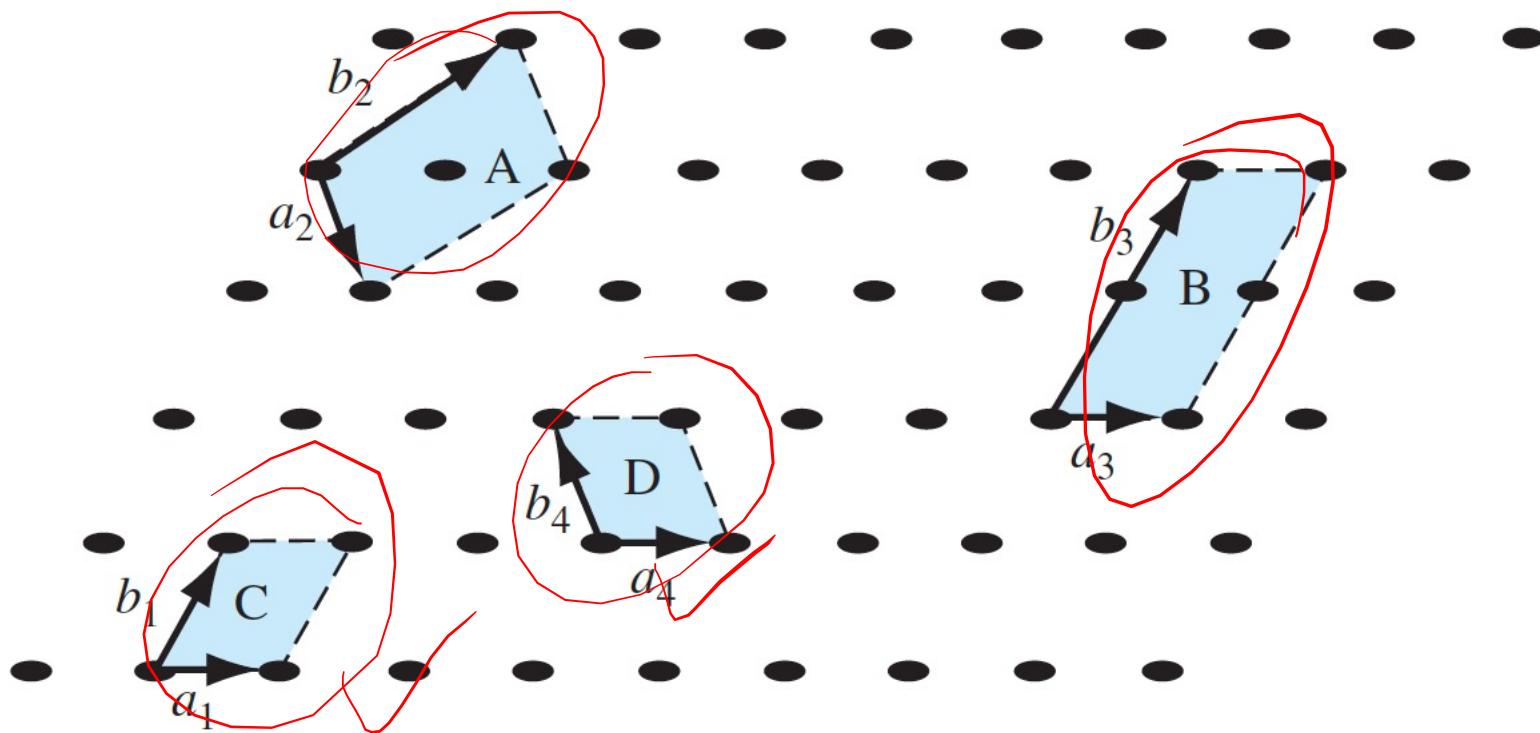
Primitive and Unit Cell



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

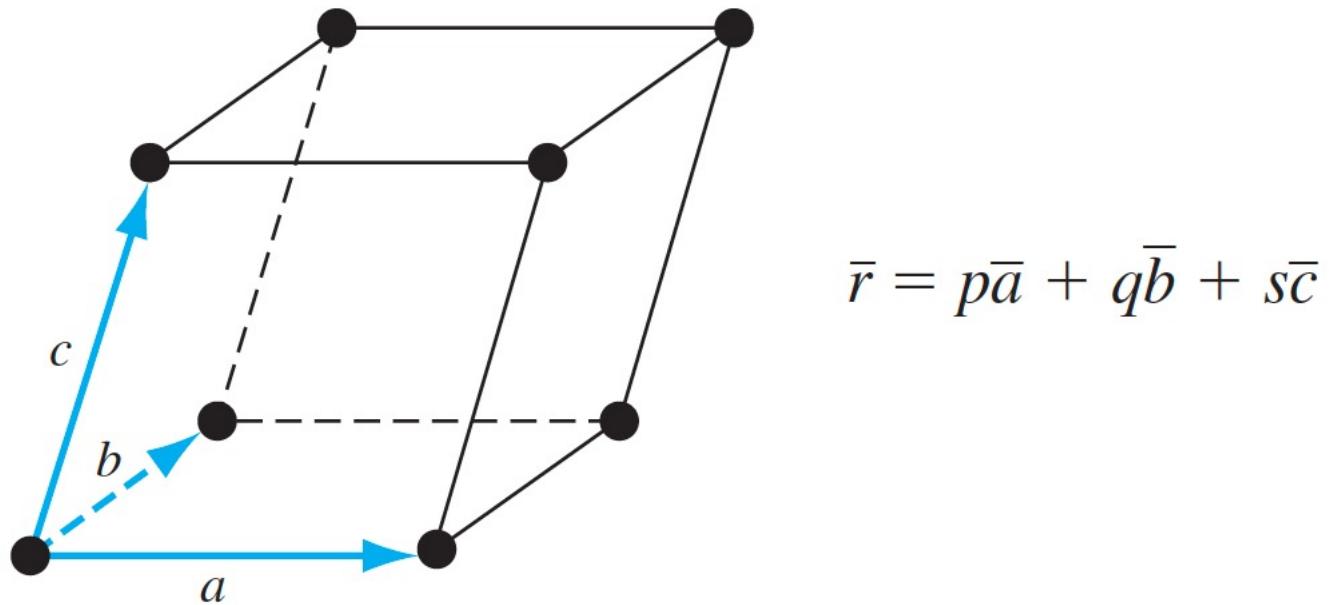
1.3 Space lattice

Primitive and Unit Cell



1.3 Space lattice

Primitive and Unit Cell



A generalized primitive unit cell

1.3 Space lattice

Basic Crystal Structures

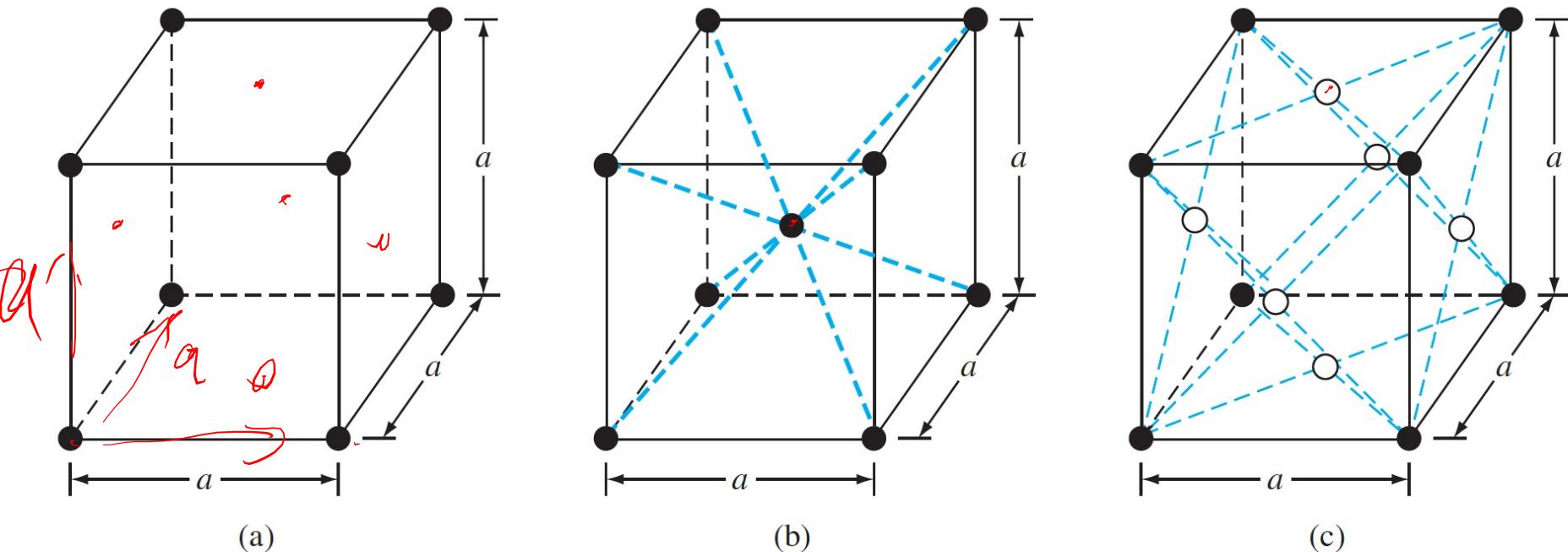


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

1.3 Space lattice

Basic Crystal Structures: volume density of atoms

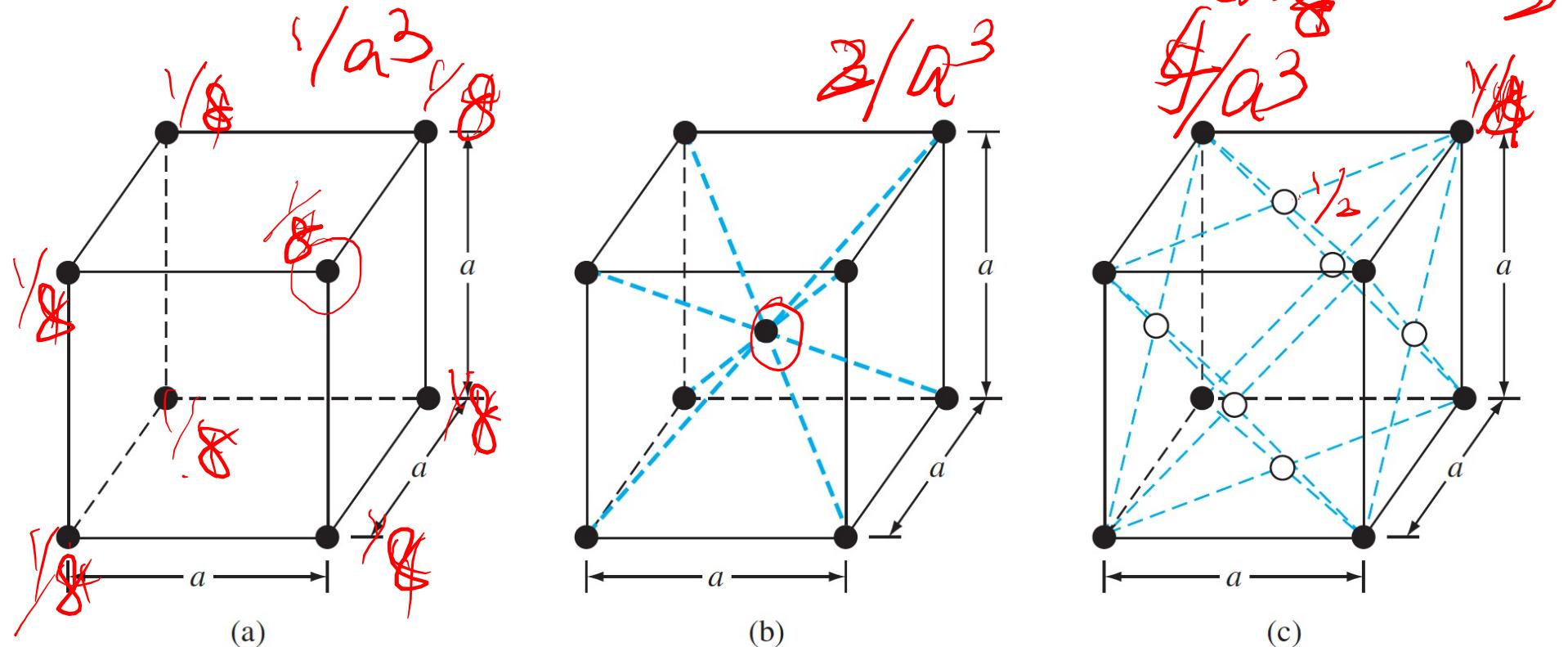
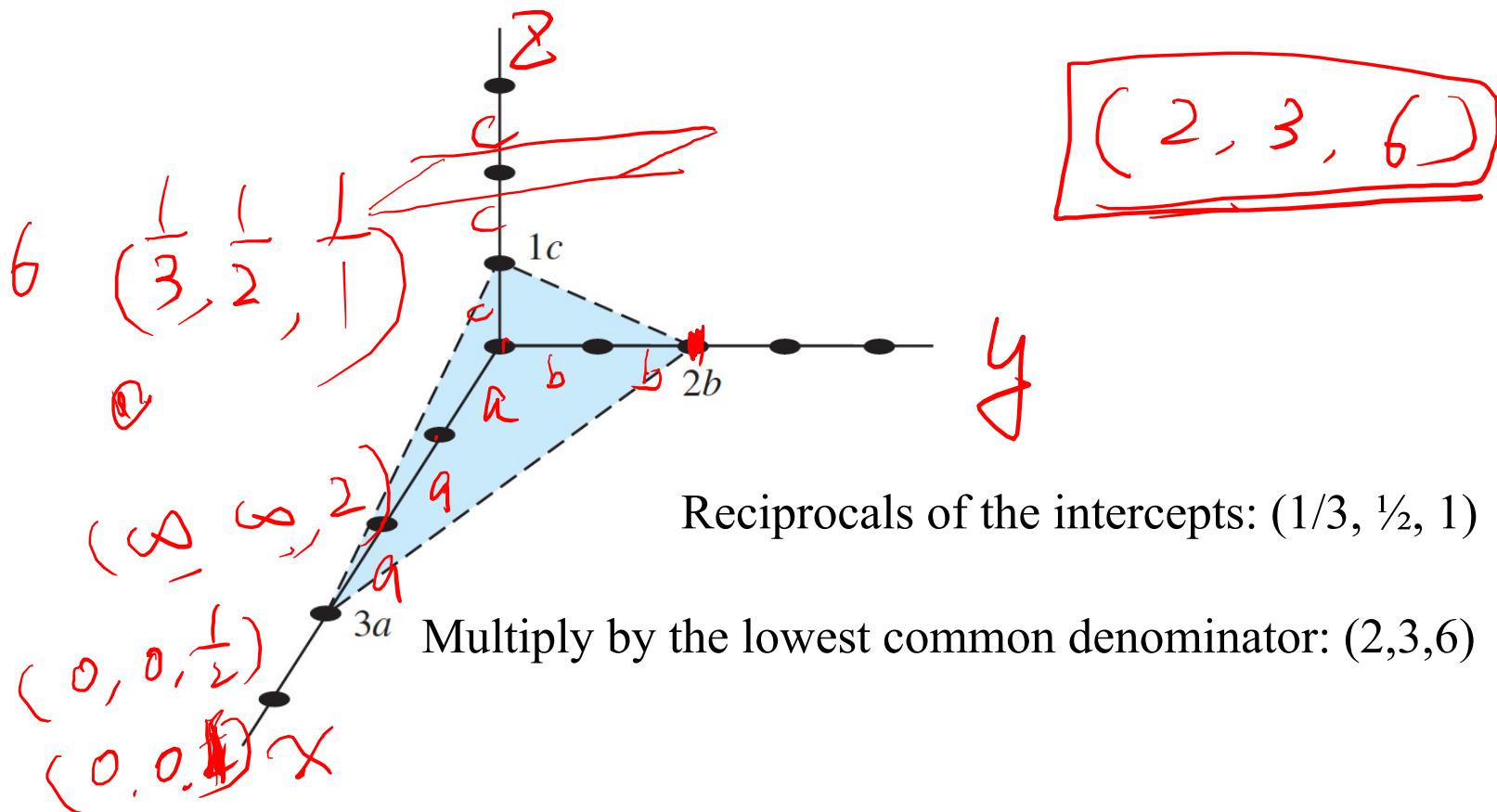


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

$$8 \times \frac{1}{8} / a^3 = 2/a^3$$

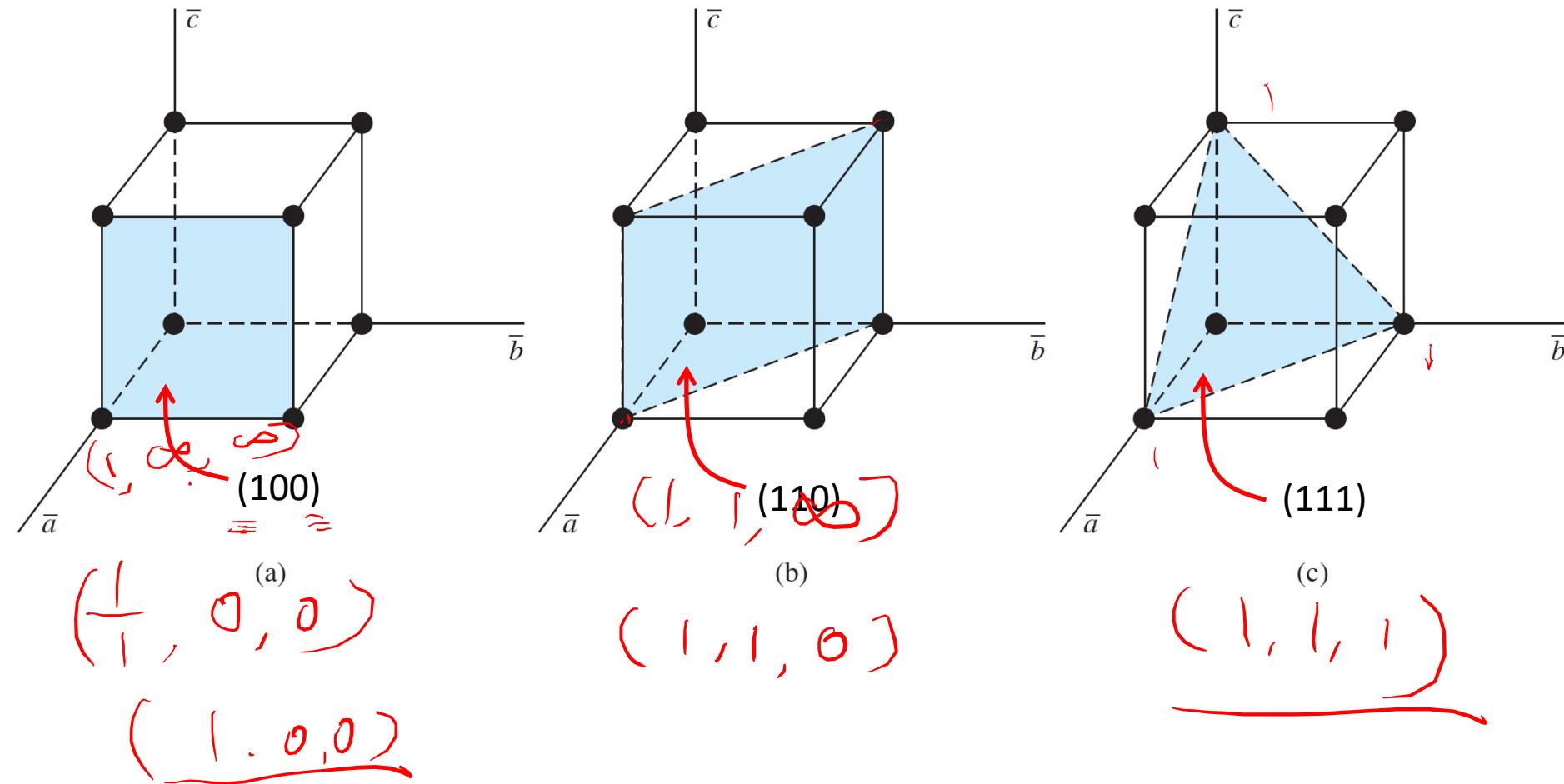
1.3 Space lattice

Crystalline Plane and Miller Index



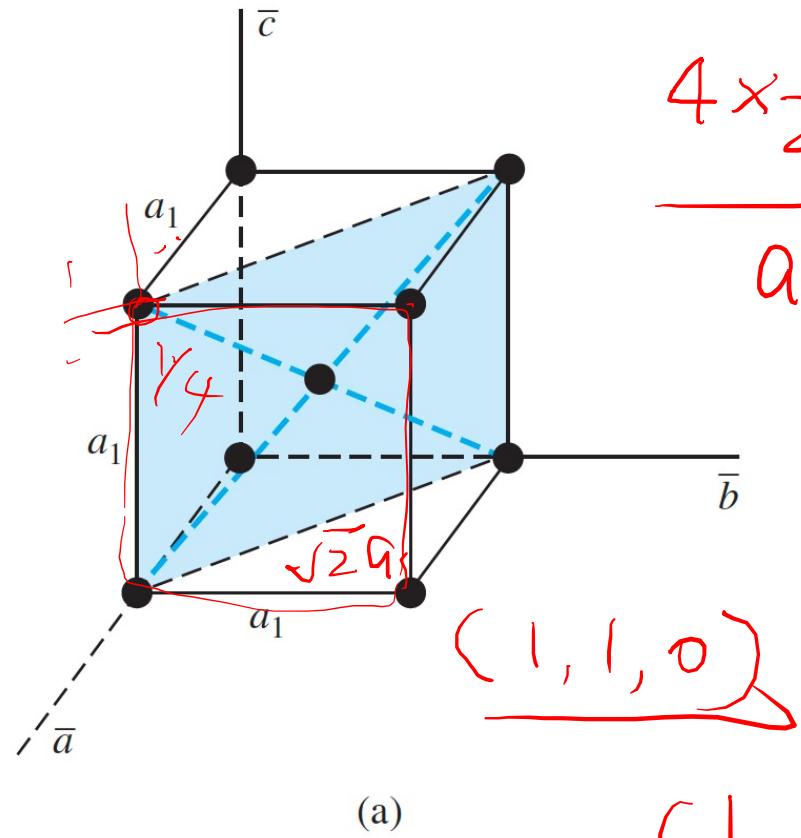
1.3 Space lattice

Crystalline Plane and Miller Index

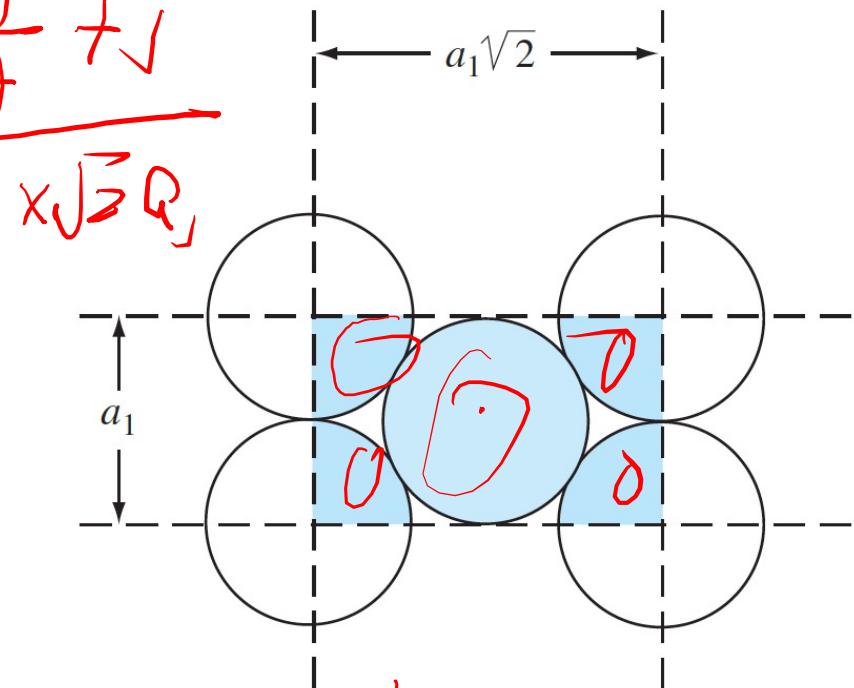


1.3 Space lattice

Crystalline Plane and Miller Index: surface density of atoms



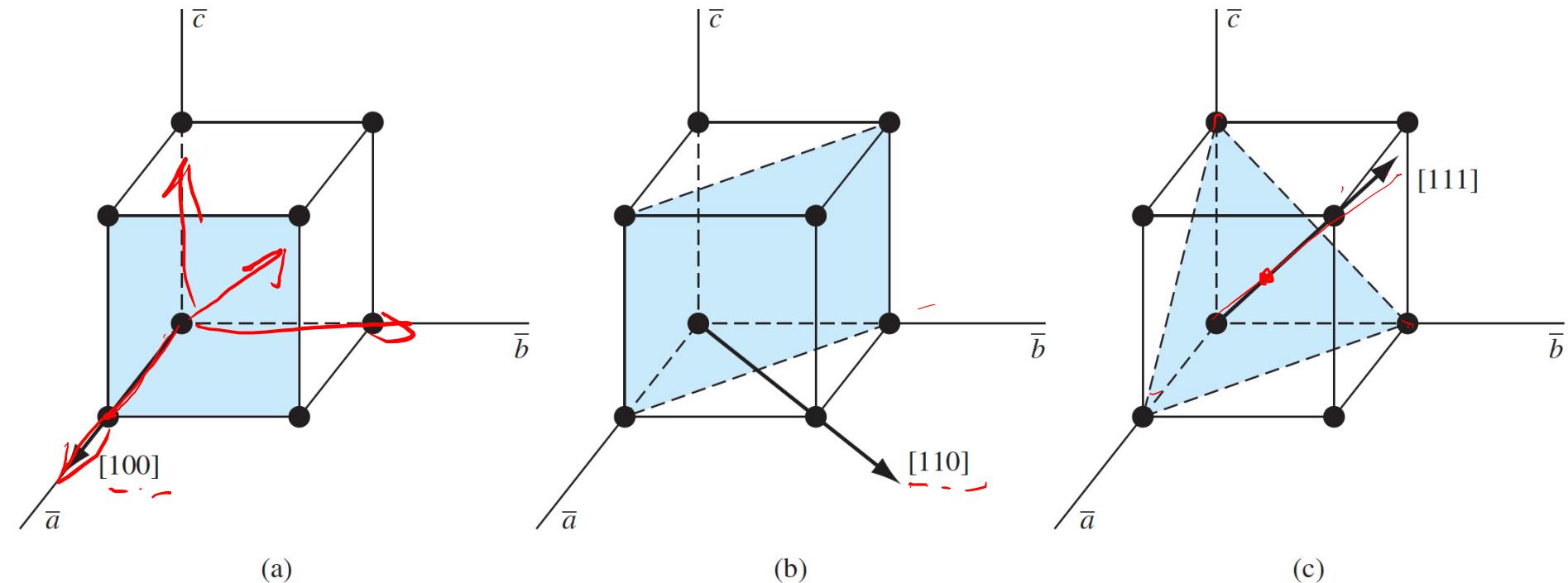
$$4 \times \frac{1}{4} + \sqrt{a_1 \times \sqrt{3} Q_1}$$



$$(1, 1, 0) \quad \frac{4 \times \frac{1}{4}}{q_1^2} \quad (b)$$

1.3 Space lattice

Directions in Crystals



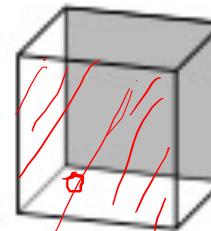
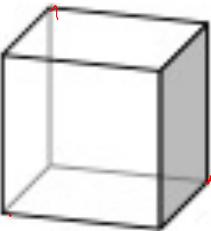
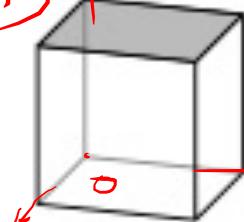
In cubic lattice: $[hkl]$ direction is perpendicular to the $\underline{(hkl)}$ plane

Check your understanding

Identify crystalline plane

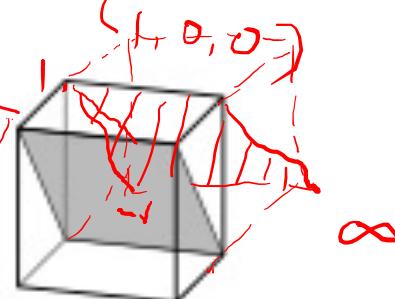
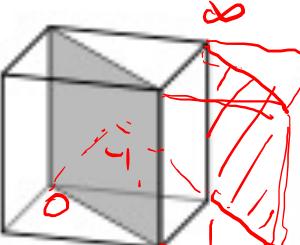
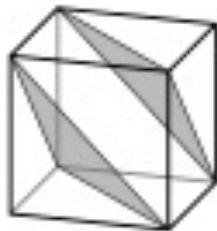
(0,1,0)

(0,0,1)

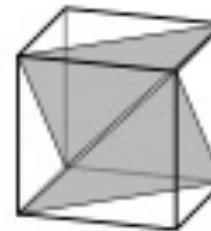


(0,1,1)

(∞ -1, 1)



(-1, 0, 1)



Outline

1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

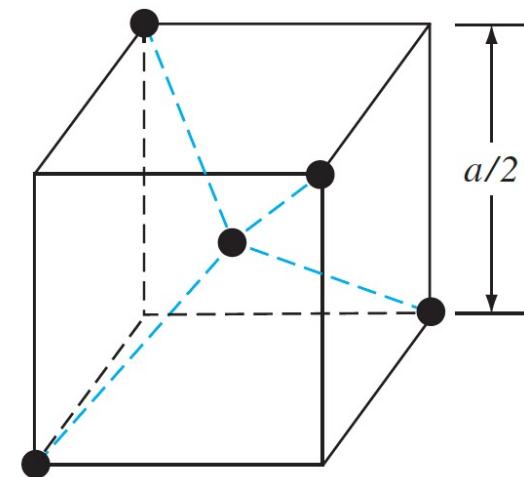
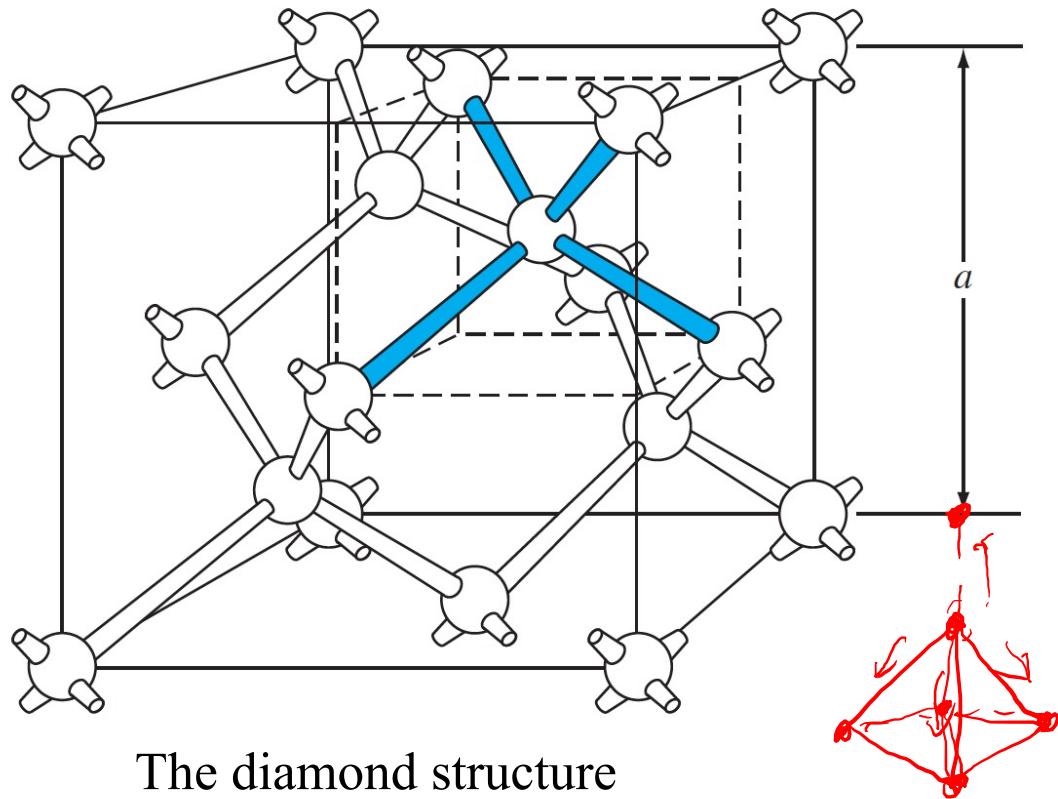


1.5 Atomic bonding

1.6 Imperfections and impurities in solids

1.4 The diamond structure

The diamond lattice

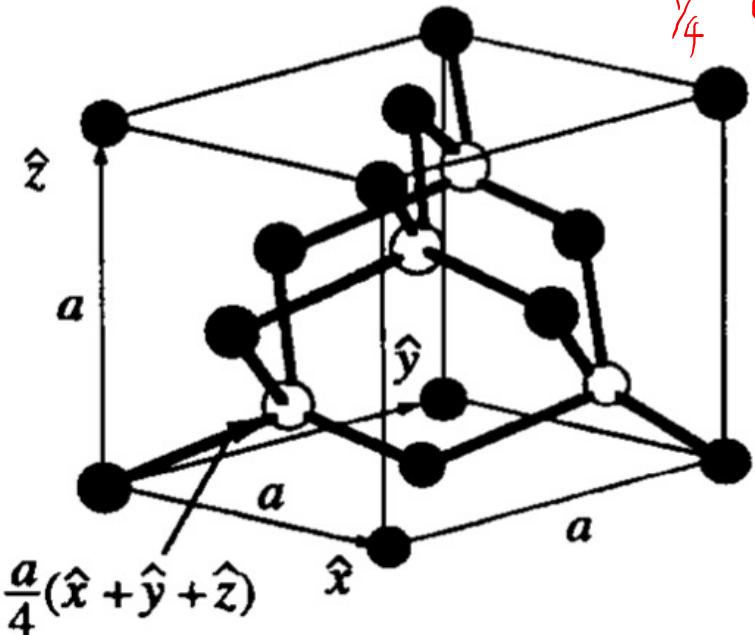


The tetrahedral structure of
closest neighbors in the diamond
lattice

1.4 The diamond structure

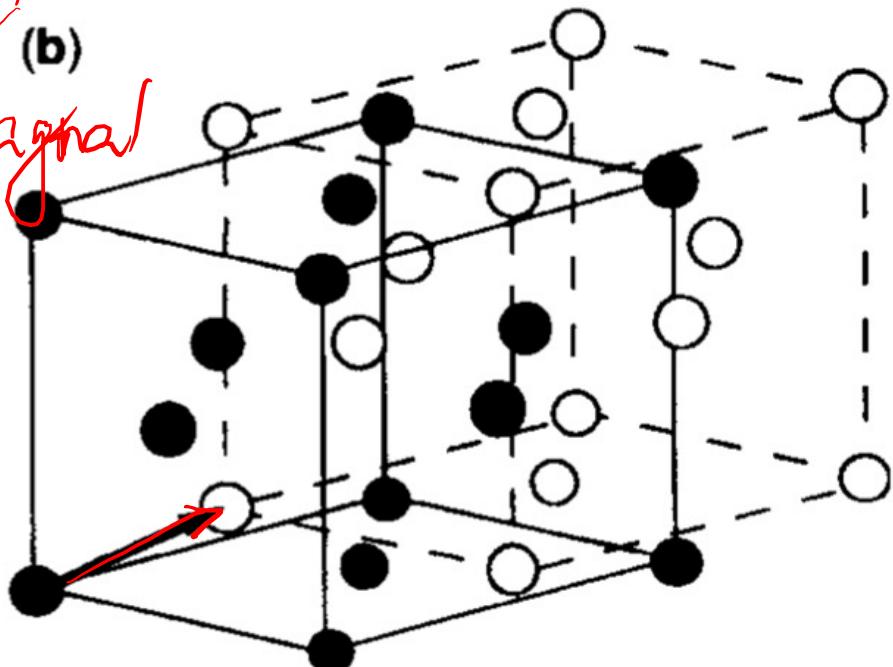
The diamond lattice

(a)



(b)

diagonal



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

1.4 The diamond structure

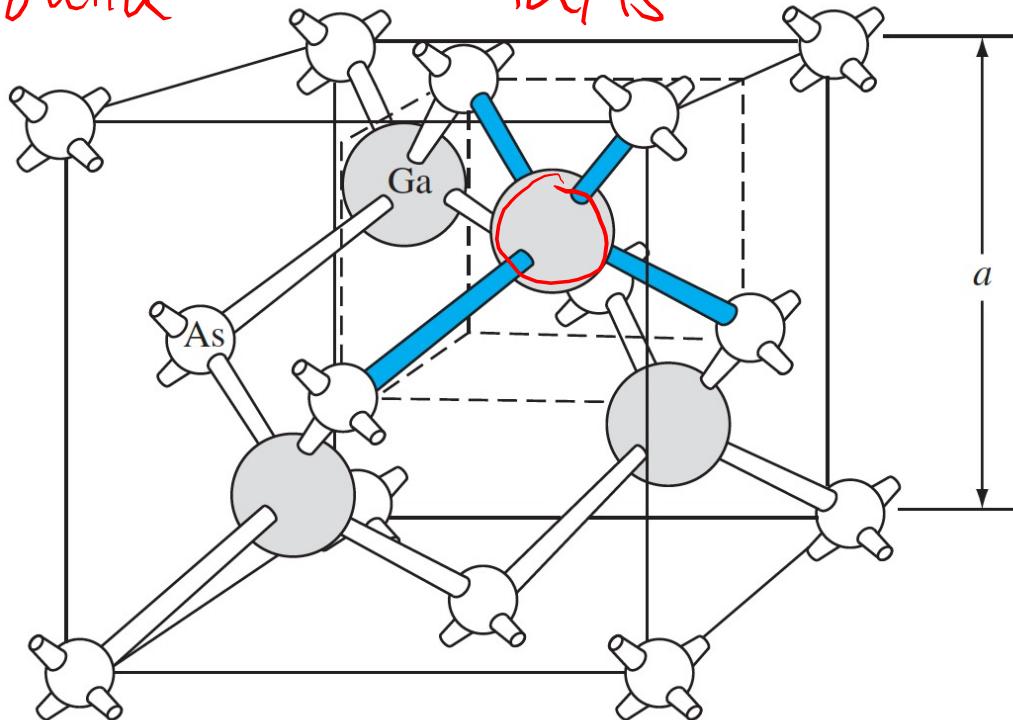
The diamond lattice (all atoms are the same)

elemental Si, Ge

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

compound

GaAs



Outline

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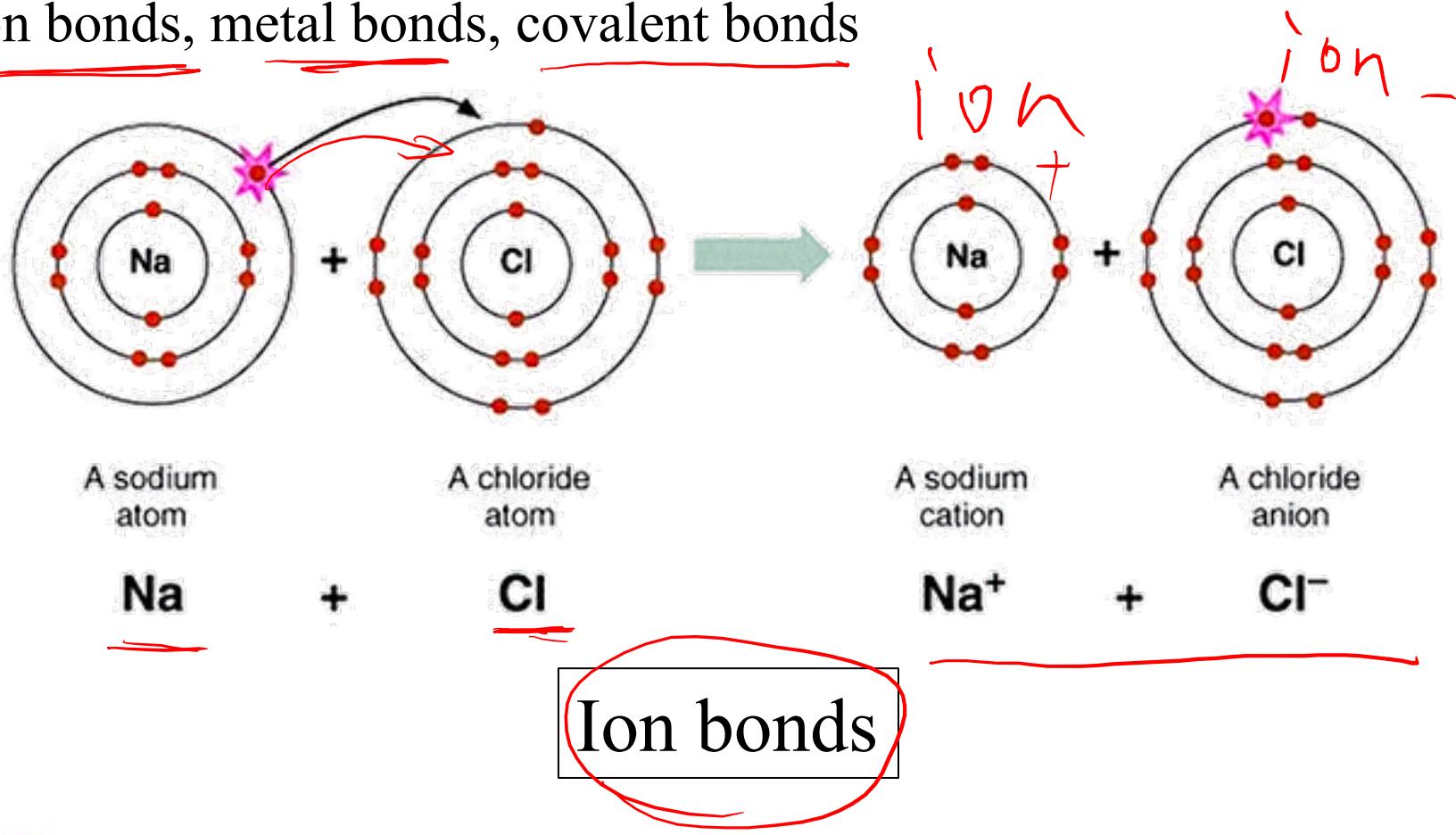
1.6 Imperfections and impurities in solids



1.5 Chemical bonds

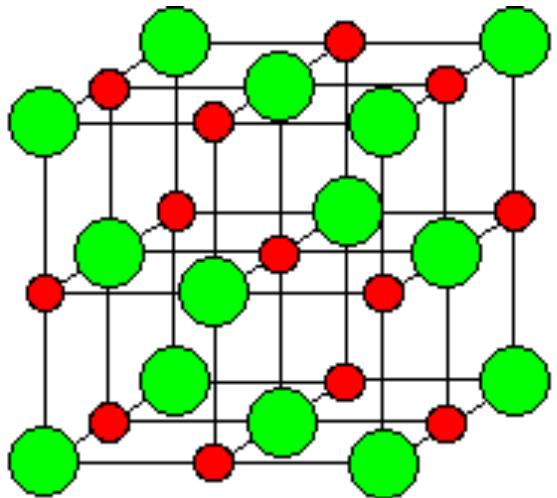
Chemical Bonds: Binding of atoms or ions

Ion bonds, metal bonds, covalent bonds

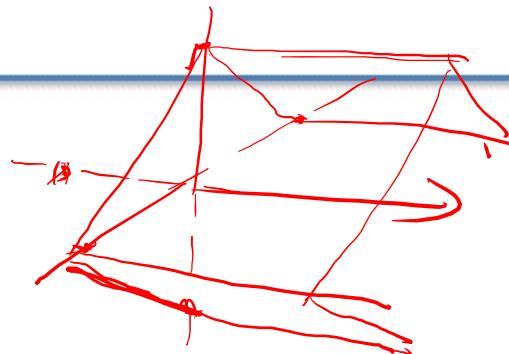
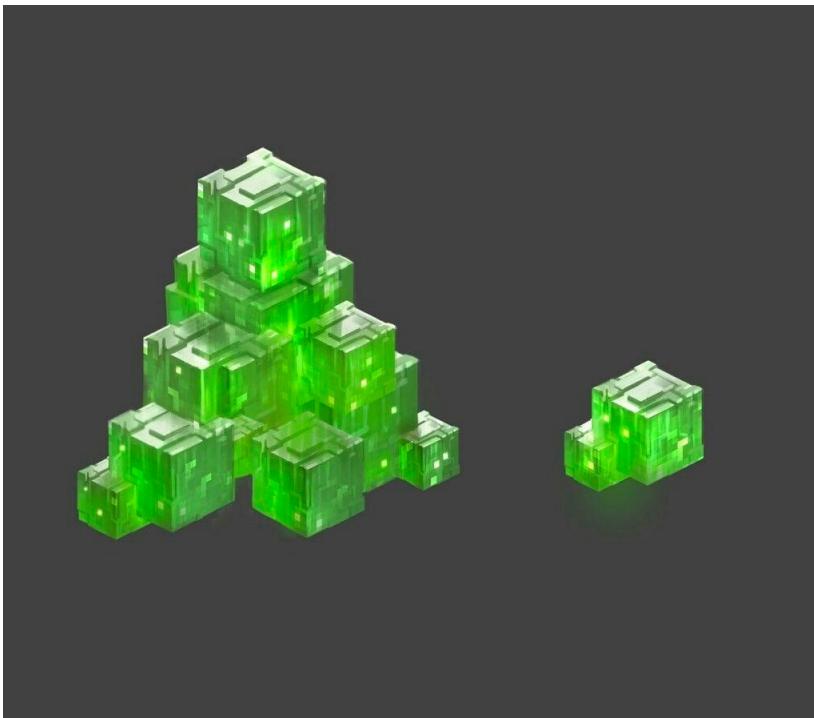


1.5 Chemical bonds

Ion Crystals

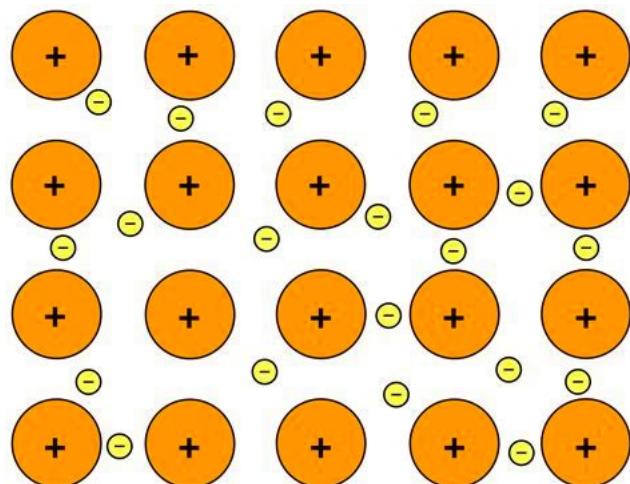
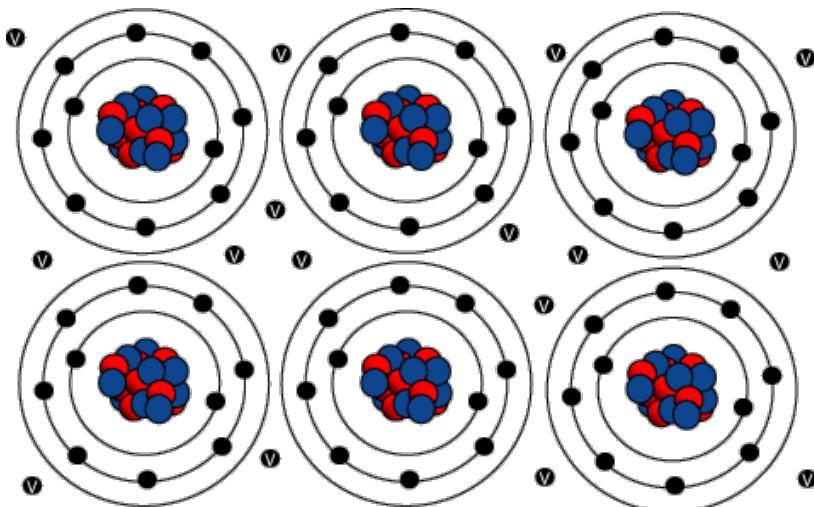


● Na^+
● Cl^-



1.5 Chemical bonds

Metal bonds



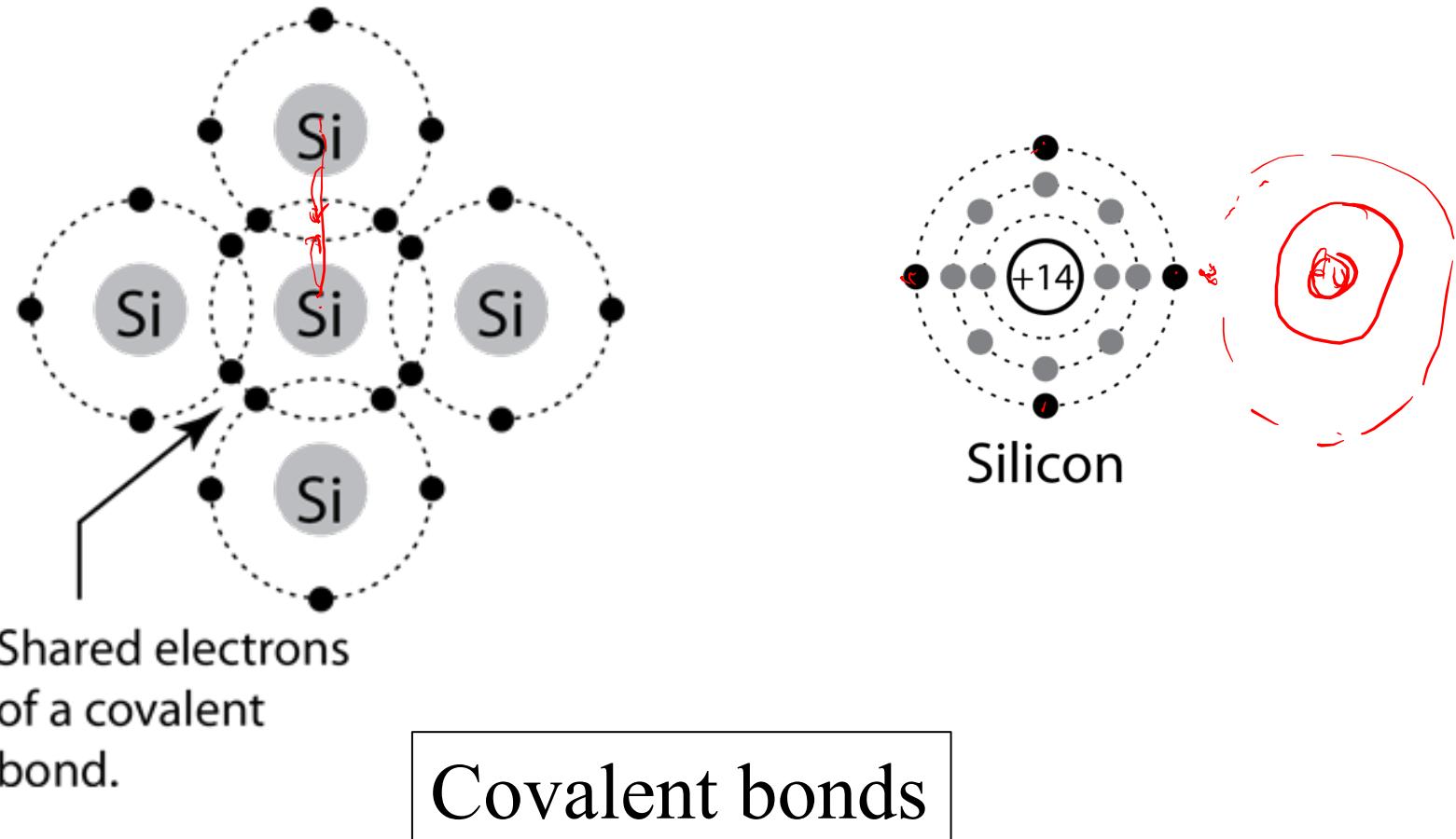
1.5 Chemical bonds

Metal Crystals



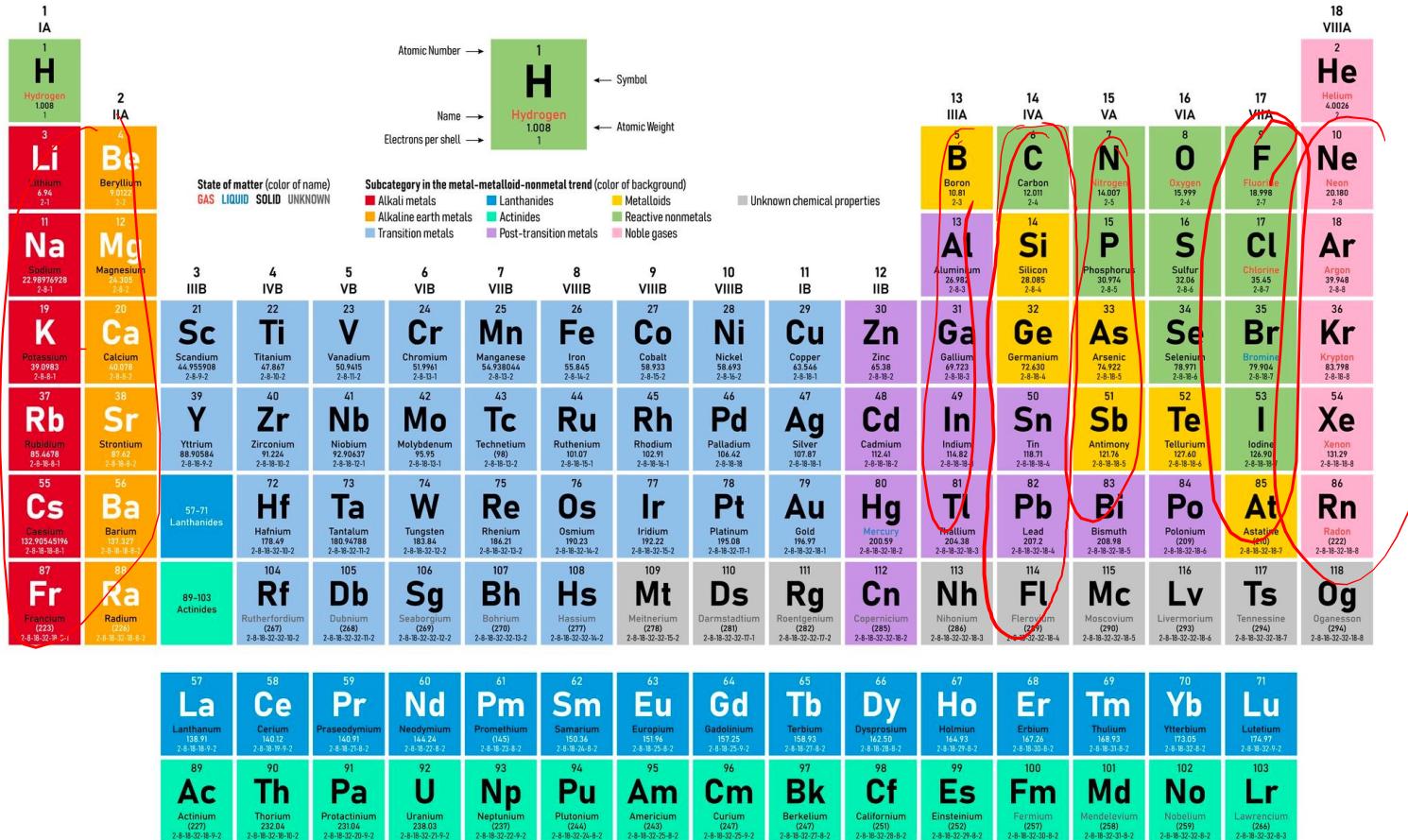
1.5 Chemical bonds

Covalent bonds: shared electrons in outer orbitals



1.5 Chemical bonds

Periodic Table of the Elements



Outline

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1.5 Atomic bonding

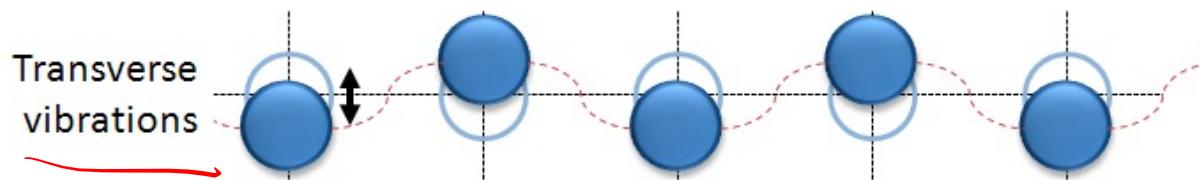
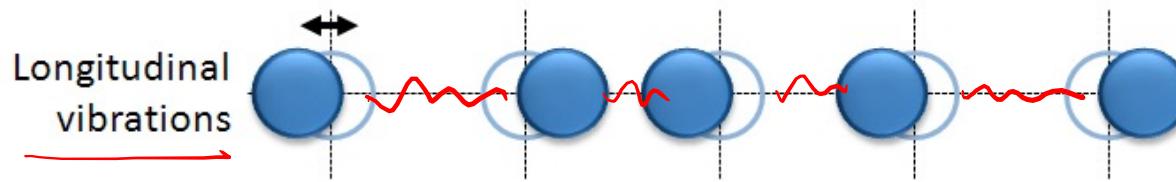
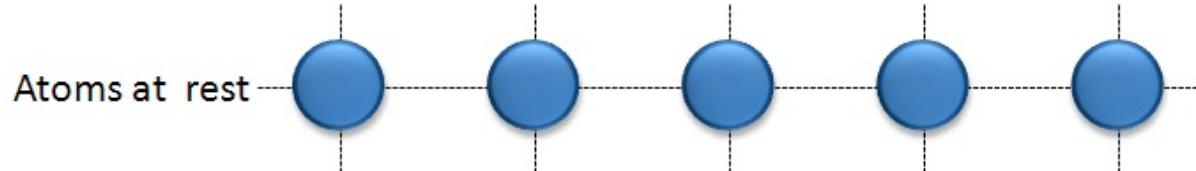
1.6 Imperfections and impurities in solids



1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations, thermal vibration or phonons



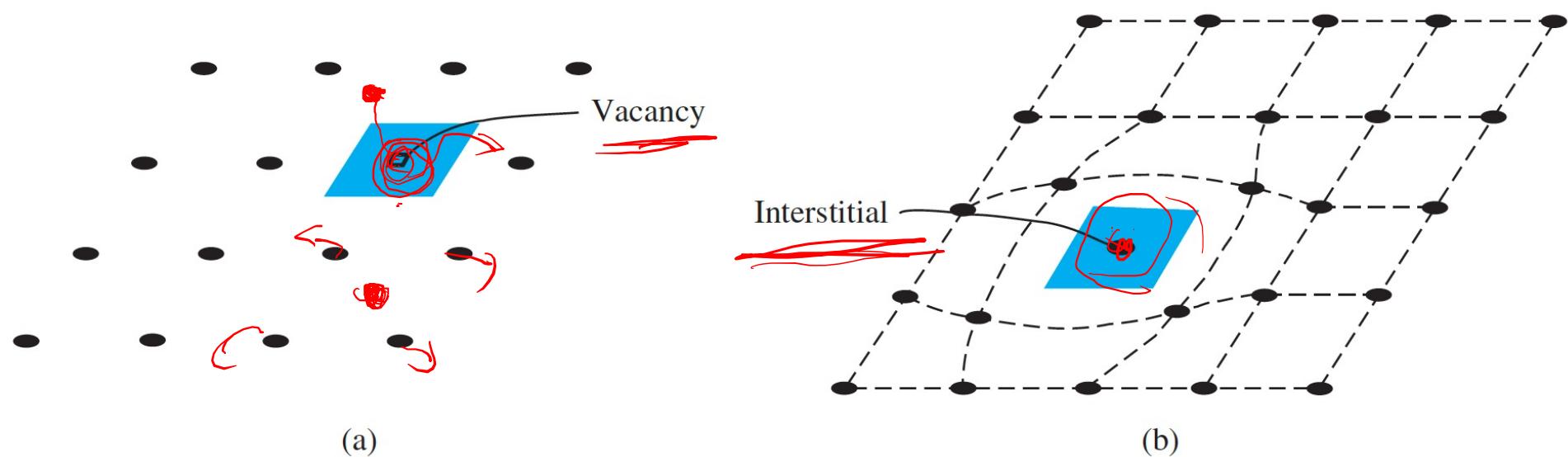
A
WAVE \leftrightarrow particle
C_e

1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

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



(a)

(b)

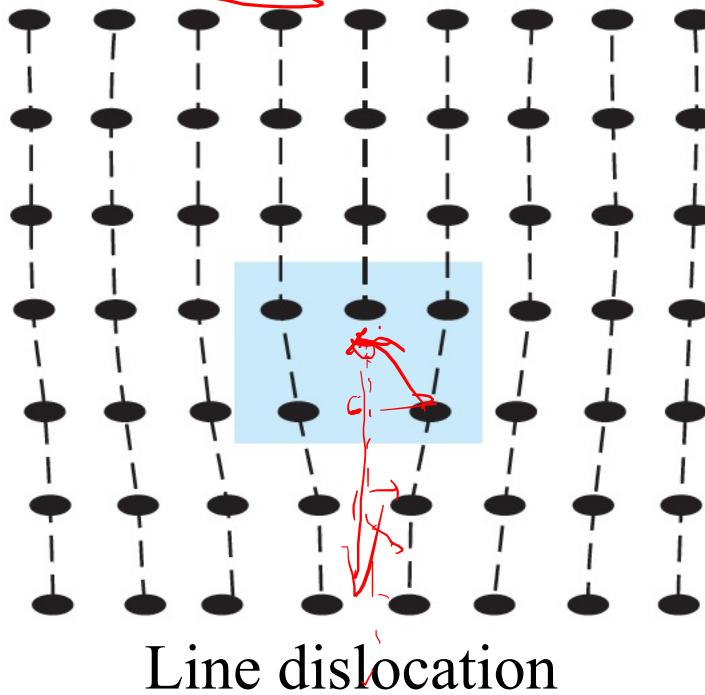
1.6 Imperfections and impurities in solids

Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

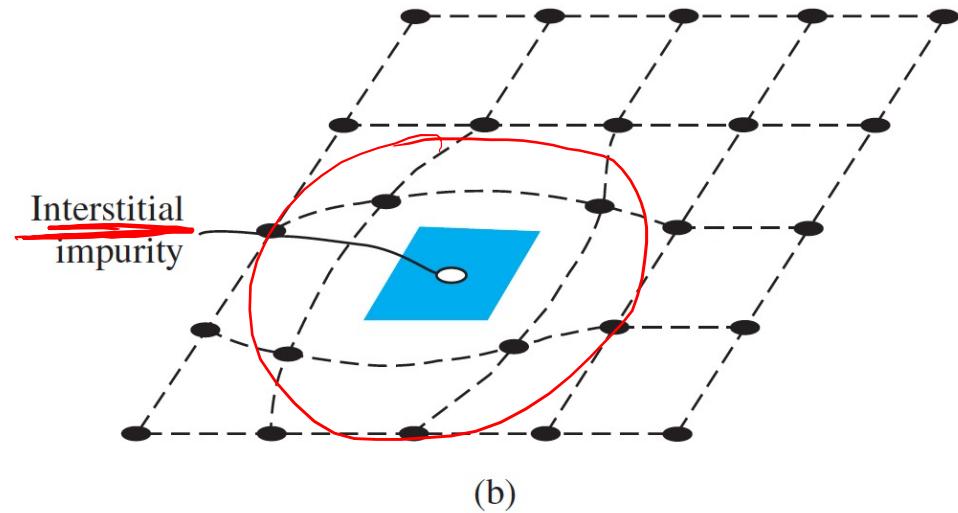
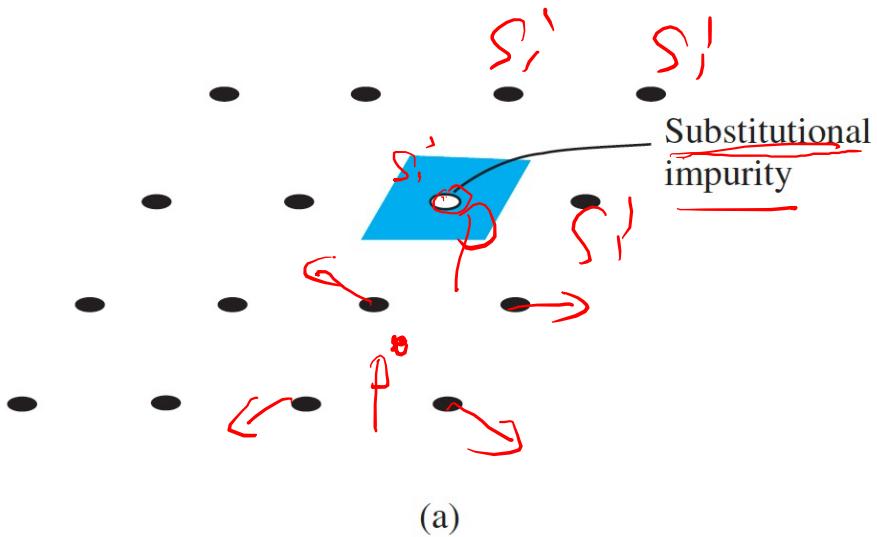
Point defects: vacancies, interstitial defects, vacancy-interstitial defects

~~Line defects: line dislocation~~



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

The Periodic Table of the Elements displays the following information for each element:

- Atomic Number →** The atomic number is shown above the element symbol.
- Name →** The element name is written below the symbol.
- Symbol** → The element symbol is enclosed in a green box.
- Electrons per shell →** The electron configuration is shown below the symbol.
- Atomic Weight →** The atomic weight is shown below the symbol.

State of matter (color of name)

- GAS (Red)
- LIQUID (Blue)
- SOLID (Green)
- UNKNOWN (Yellow)

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

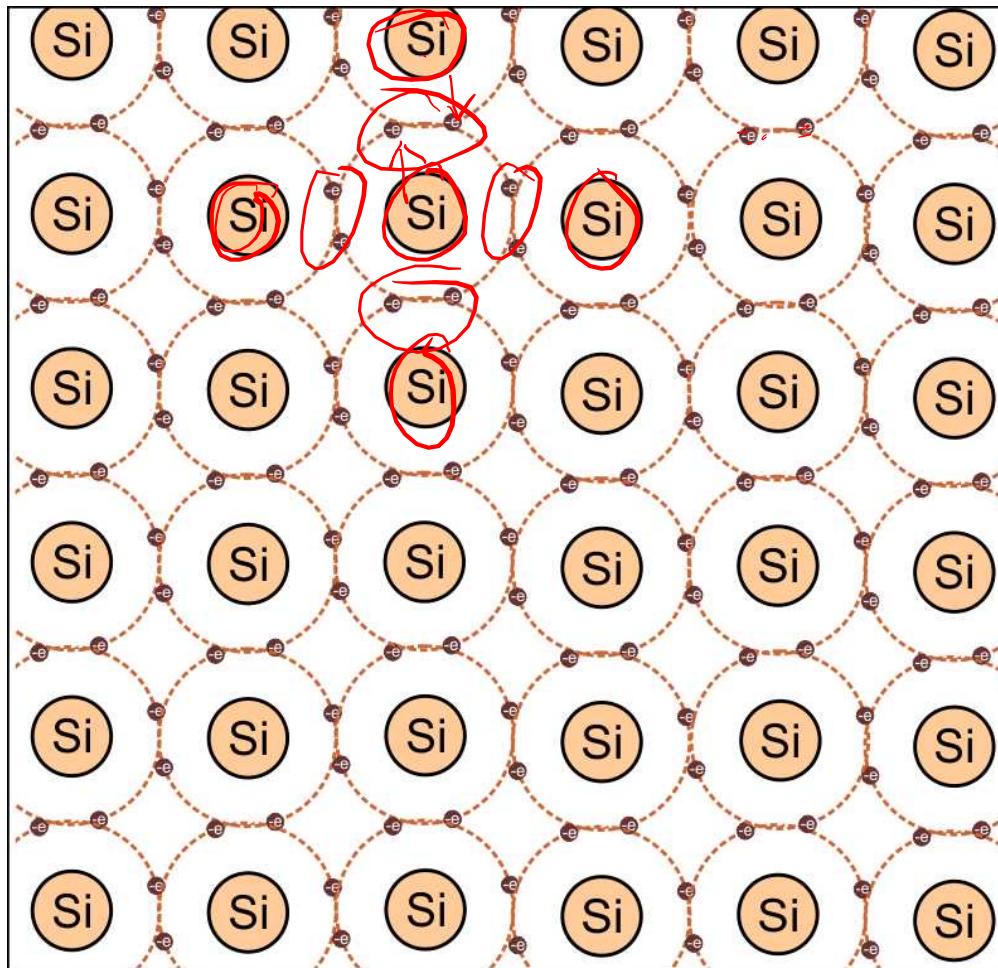
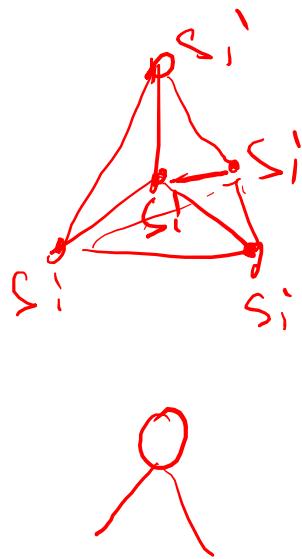
- Alkali metals (Red)
- Alkaline earth metals (Orange)
- Transition metals (Blue)
- Lanthanides (Dark Blue)
- Metalloids (Yellow)
- Post-transition metals (Purple)
- Actinides (Teal)
- Reactive nonmetals (Green)
- Noble gases (Pink)

Unknown chemical properties (Grey box)

p-type	n-type
Boron (B) 10.81 2.3	Carbon (C) 12.01 2.4
Phosphorus (P) 30.974 2.8-5	Sulfur (S) 32.06 2.8-4
Silicon (Si) 28.09 2.8-4	Chlorine (Cl) 35.45 2.8-7
Germanium (Ge) 72.61 2.8-3.4	Bromine (Br) 79.904 2.8-3.7
Antimony (Sb) 75.971 2.8-3.6	Krypton (Kr) 83.80 2.8-3.8
Tin (Sn) 118.71 2.8-3.5	Iodine (I) 126.90 2.8-3.8
Lead (Pb) 208.98 2.8-3.8-4.5	Xenon (Xe) 131.29 2.8-3.8-6
Bismuth (Bi) 208.98 2.8-3.8-4.5	Radon (Rn) 222 2.8-3.8-6
Potassium (K) 39.09 2.8-3.8	



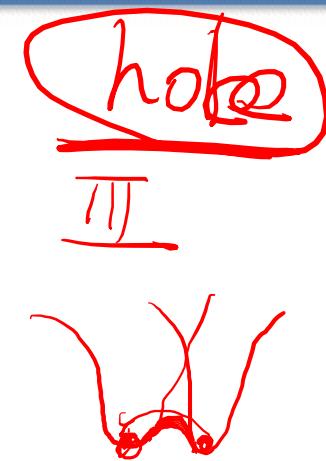
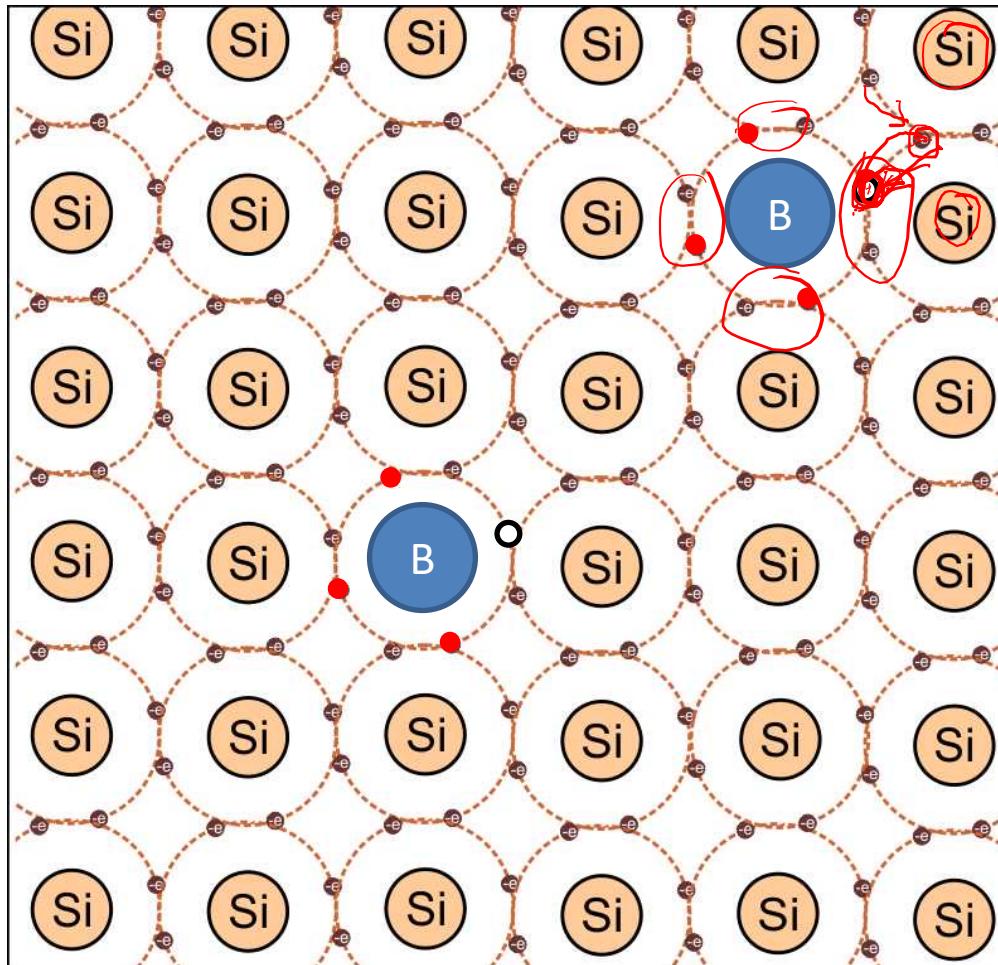
1.6 Imperfections and impurities in solids



1.6 Imperfections and impurities in solids

p-type
doping

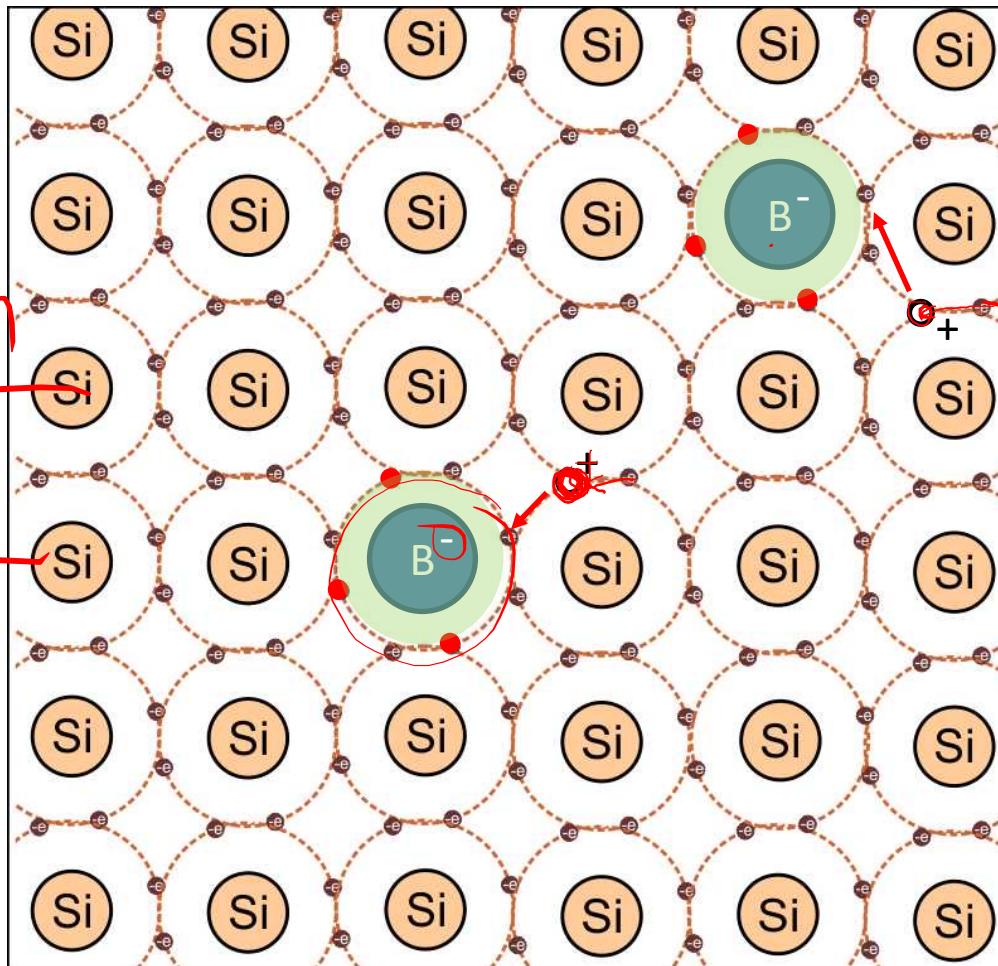
positive



1.6 Imperfections and impurities in solids

p-type
doping

~~- taken
drug~~

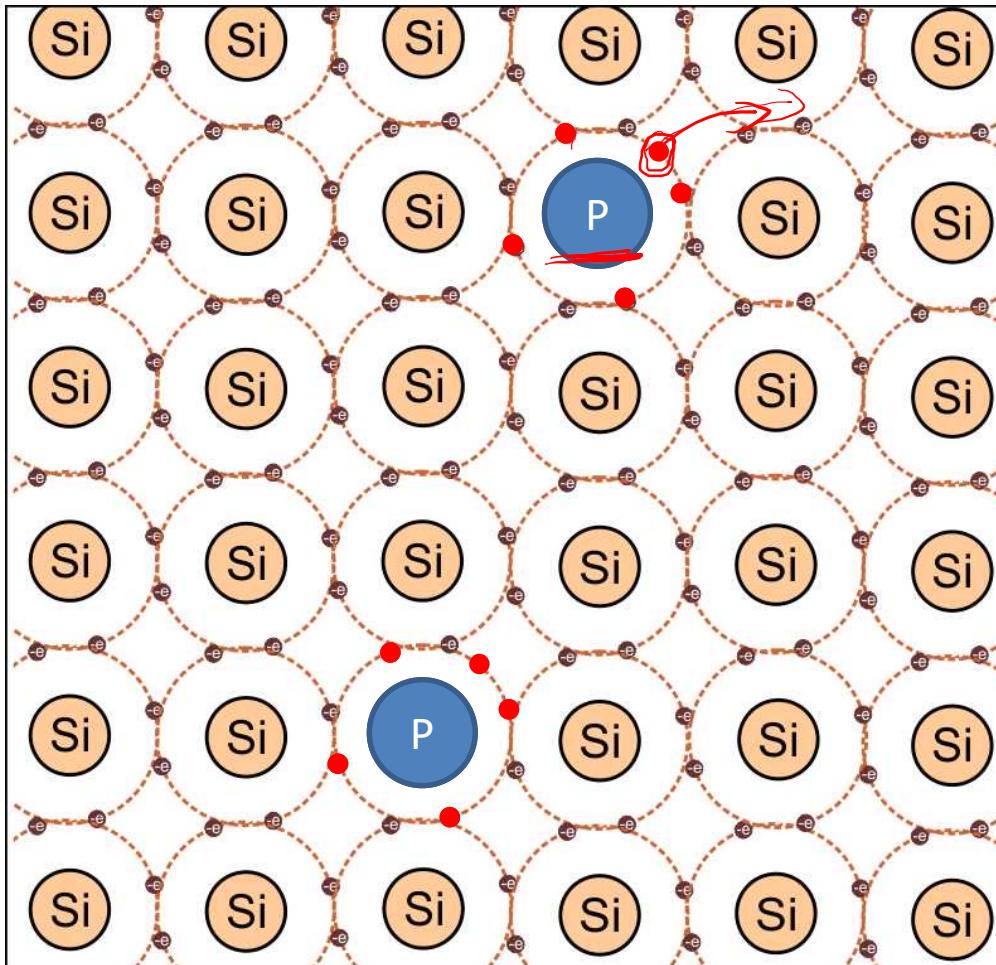


Acceptor-type of doping

1.6 Imperfections and impurities in solids

n-type
doping

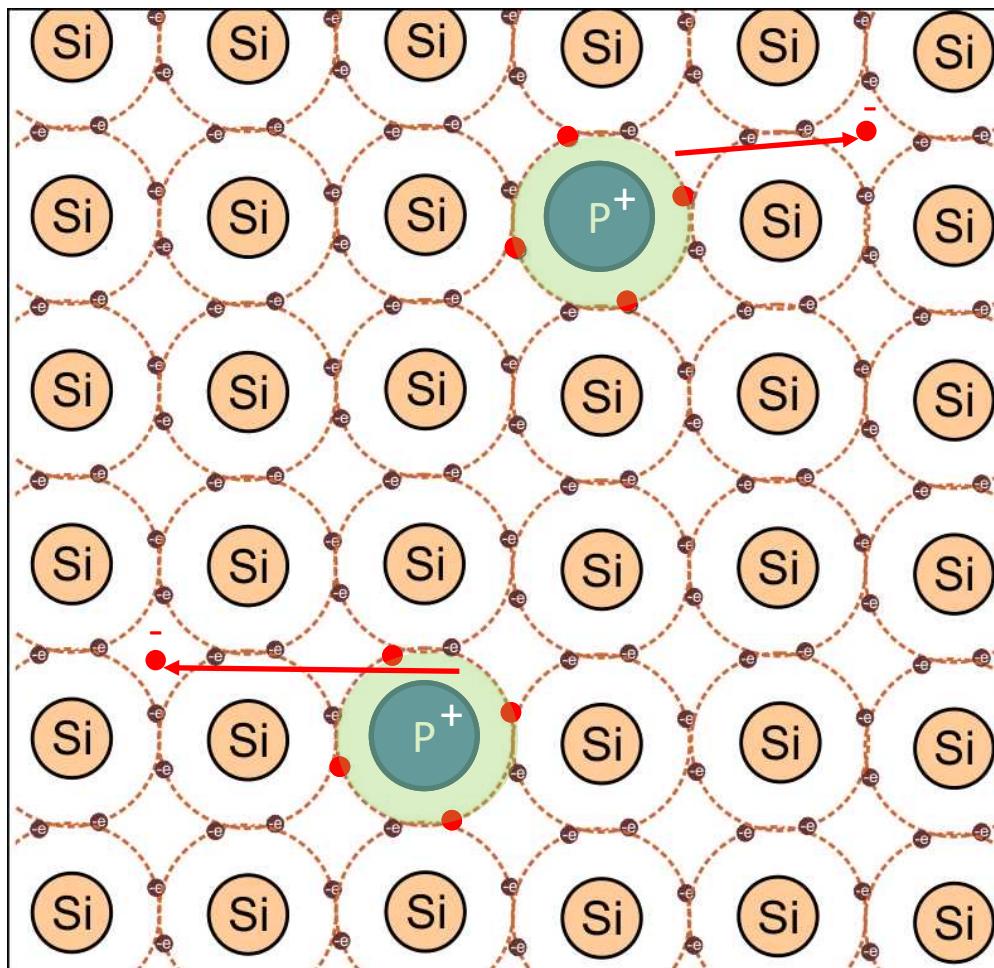
negative



Donor-type of doping

1.6 Imperfections and impurities in solids

n-type
doping

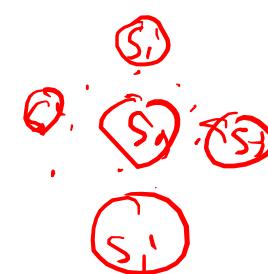


Donor-type of doping

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



1 IA	H Hydrogen 1.008 1	2 IIA	
Li Lithium 6.94 3 2.5	Be Beryllium 9.012 4		
Na Potassium 39.0983 19 2.8-8.1	Mg Magnesium 22.9877028 20 2.8-8.1		
K Calcium 40.078 21 2.8-8.1	Ca Calcium 40.078 20 2.8-8.1	Sc Scandium 44.955708 21 2.8-8.2	Ti Titanium 47.874 22 2.8-8-2
Rb Rubidium 85.4678 37 2.8-8-8.1	Sr Strontium 84.670284 38 2.8-8-8.1	V Vanadium 50.945 23 2.8-8-2	Cr Chromium 54.93804 24 2.8-8-2
Cs Cesium 132.9054594 55 2.8-8-8.1	Ba Barium 137.32 56 2.8-8-8.1	Mn Manganese 54.93804 25 2.8-8-2	Fe Iron 55.845 26 2.8-8-2
Fr Francium (223) 87 2.8-8-8.1	Ra Radium (226) 88 2.8-8-8.1	Tc Technetium 98.91197 40 2.8-8-10-2	Ru Ruthenium 101.923 41 2.8-8-10-2
Ac Actinium (227) 89 2.8-8-8-8.1	Rf Rutherfordium (267) 104 2.8-8-8-8-8.1	Hf Hafnium 178.49 72 2.8-8-10-2	Ta Tantalum 180.97088 73 2.8-8-10-2
Th Thorium (232) 90 2.8-8-8-8.1	Db Dubnium (268) 105 2.8-8-8-8-8.1	W Tungsten 183.84 74 2.8-8-10-2	R Rhenium 186.21 75 2.8-8-10-2
Pa Protactinium (231) 91 2.8-8-8-8.1	Sg Seaborgium (269) 106 2.8-8-8-8-8.1	Os Osmium 195.03 76 2.8-8-10-2	Ir Iridium 192.22 77 2.8-8-10-2
U Uranium (238) 92 2.8-8-8-8.1	Bh Bohrium (270) 107 2.8-8-8-8-8.1	Pt Platinum 191.02 78 2.8-8-10-2	Pt Platinum 191.02 79 2.8-8-10-2
Np Neptunium (237) 93 2.8-8-8-8.1	Hs Hassium (272) 108 2.8-8-8-8-8.1	Au Gold 196.97 80 2.8-8-10-2	Hg Mercury 200.59 81 2.8-8-10-2
Pu Plutonium (244) 94 2.8-8-8-8.1	Mt Mendelevium (278) 109 2.8-8-8-8-8.1	Ds Darmstadtium (281) 110 2.8-8-8-8-8.1	Tl Thallium 204.38 82 2.8-8-10-2
Am Americium (243) 95 2.8-8-8-8.1	Rg Roentgenium (282) 111 2.8-8-8-8-8.1	Cn Copernicium (285) 112 2.8-8-8-8-8.1	Pb Lead 207.2 83 2.8-8-8-8.1
Cm Curium (247) 96 2.8-8-8-8.1	Dy Dysprosium 162.50 65 2.8-8-8-8.1	Nh Nihonium (286) 113 2.8-8-8-8-8.1	Bi Bismuth 208.98 84 2.8-8-8-8.1
Bk Berkelium (247) 97 2.8-8-8-8.1	Tb Terbium 158.93 64 2.8-8-8-8.1	Fl Flerovium (289) 114 2.8-8-8-8-8.1	Po Polonium (209) 85 2.8-8-8-8.1
Cf Curium (247) 98 2.8-8-8-8.1	Dy Dysprosium 162.50 66 2.8-8-8-8.1	Mc Moscovium (290) 115 2.8-8-8-8-8.1	At Astatine (210) 86 2.8-8-8-8.1
Es Einsteinium (252) 99 2.8-8-8-8.1	Ho Holmium 164.93 67 2.8-8-8-8.1	Lv Livermorium (293) 116 2.8-8-8-8-8.1	Rn Radium (223) 87 2.8-8-8-8.1
Fm Fermium (257) 100 2.8-8-8-8.1	Er Erthium 167.26 68 2.8-8-8-8.1	Ts Tennessine (294) 117 2.8-8-8-8-8.1	
Md Mendelevium (258) 101 2.8-8-8-8.1	Tm Thulium 168.93 69 2.8-8-8-8.1	Og Oganesson (294) 118 2.8-8-8-8.1	
No Neptunium (259) 102 2.8-8-8-8.1	Yb Ytterbium 173.05 70 2.8-8-8-8.1	Lu Lutetium 174.97 71 2.8-8-8-8.1	
Lr Lawrencium (260) 103 2.8-8-8-8.1			

