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**VE320 – Summer 2021**

**Introduction to Semiconductor Devices**

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**Chapter 1 Crystalline structure of solids**

# Outline

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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

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## **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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## 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 <sub>2</sub> , HfO <sub>2</sub> ...
Solids, liquids (Hg)	Solids	Solids, liquids gases

# 1.1 Semiconductor materials

## Periodic Table of the Elements

<div>Atomic Number →</div> <div>← Symbol</div> <div>Name →</div> <div>Electrons per shell →</div> <div>Atomic Weight</div>																	
<div>State of matter (color of name) GAS LIQUID SOLID UNKNOWN</div> <div>Subcategory in the metal-metalloid-nonmetal trend (color of background) Alkali metals Lanthanides Metalloids Alkaline earth metals Actinides Reactive nonmetals Transition metals Post-transition metals Noble gases Unknown chemical properties</div>																	
<div>13 IIIA 5 B Boron 10.81 2.3</div> <div>14 IVA 6 C Carbon 12.011 2.4</div> <div>15 VA 7 N Nitrogen 14.007 2.5</div> <div>16 VIA 8 O Oxygen 15.999 2.4</div> <div>17 VIIA 9 F Fluorine 18.998 2.7</div> <div>18 VIIIA 2 He Helium 4.0026 2</div>																	
<div>13 IIIA 13 Al Aluminum 26.982 2.8-3</div> <div>14 IVA 14 Si Silicon 28.085 2.8-4</div> <div>15 VA 15 P Phosphorus 30.974 2.8-5</div> <div>16 VIA 16 S Sulfur 32.06 2.8-4</div> <div>17 VIIA 17 Cl Chlorine 35.45 2.8-7</div> <div>18 VIIIA 10 Ne Neon 20.180 2.8</div>																	
<div>13 IIIA 31 Ga Gallium 69.723 2.8-9-3</div> <div>14 IVA 32 Ge Germanium 72.630 2.8-4</div> <div>15 VA 33 As Arsenic 74.922 2.8-5</div> <div>16 VIA 34 Se Selenium 78.971 2.8-6</div> <div>17 VIIA 35 Br Bromine 79.904 2.8-8-7</div> <div>18 VIIIA 18 Ar Argon 39.948 2.8-8</div>																	
<div>13 IIIA 49 In Indium 114.82 2.8-9-3</div> <div>14 IVA 50 Sn Tin 118.71 2.8-9-4</div> <div>15 VA 51 Sb Antimony 121.76 2.8-9-5</div> <div>16 VIA 52 Te Tellurium 127.60 2.8-9-4</div> <div>17 VIIA 53 I Iodine 126.90 2.8-9-7</div> <div>18 VIIIA 36 Kr Krypton 83.798 2.8-9-8</div>																	
<div>13 IIIA 81 Tl Thallium 204.38 2.8-9-3-5</div> <div>14 IVA 82 Pb Lead 207.2 2.8-9-3-4</div> <div>15 VA 83 Bi Bismuth 208.98 2.8-9-3-5</div> <div>16 VIA 84 Po Polonium 209 2.8-9-3-6</div> <div>17 VIIA 85 At Astatine 210 2.8-9-3-7</div> <div>18 VIIIA 54 Xe Xenon 131.29 2.8-9-8</div>																	
<div>13 IIIA 113 Nh Nihonium 284 2.8-9-3-5</div> <div>14 IVA 114 Fl Flerovium 289 2.8-9-3-4</div> <div>15 VA 115 Mc Moscovium 288 2.8-9-3-5</div> <div>16 VIA 116 Lv Livermorium 293 2.8-9-3-6</div> <div>17 VIIA 117 Ts Tennessine 294 2.8-9-3-7</div> <div>18 VIIIA 118 Og Oganesson 294 2.8-9-3-8</div>																	

57 La Lanthanum 138.91 2.8-9-32-9-2	58 Ce Cerium 140.12 2.8-9-32-9-2	59 Pr Praseodymium 140.91 2.8-9-32-9-2	60 Nd Neodymium 144.24 2.8-9-32-9-2	61 Pm Promethium (145) 145 2.8-9-32-9-2	62 Sm Samarium 150.36 2.8-9-32-9-2	63 Eu Europium 151.96 2.8-9-32-9-2	64 Gd Gadolinium 157.25 2.8-9-32-9-2	65 Tb Terbium 158.93 2.8-9-32-9-2	66 Dy Dysprosium 162.50 2.8-9-32-9-2	67 Ho Holmium 164.93 2.8-9-32-9-2	68 Er Erbium 167.26 2.8-9-32-9-2	69 Tm Thulium 168.93 2.8-9-32-9-2	70 Yb Ytterbium 173.05 2.8-9-32-9-2	71 Lu Lutetium 174.97 2.8-9-32-9-2
89 Ac Actinium (227) 227 2.8-9-32-9-2	90 Th Thorium 232.04 2.8-9-32-9-2	91 Pa Protactinium 231.04 2.8-9-32-9-2	92 U Uranium 238.03 2.8-9-32-9-2	93 Np Neptunium (237) 237 2.8-9-32-9-2	94 Pu Plutonium (244) 244 2.8-9-32-9-2	95 Am Americium (243) 243 2.8-9-32-9-2	96 Cm Curium (247) 247 2.8-9-32-9-2	97 Bk Berkelium (247) 247 2.8-9-32-9-2	98 Cf Californium (251) 251 2.8-9-32-9-2	99 Es Einsteinium (252) 252 2.8-9-32-9-2	100 Fm Fermium (257) 257 2.8-9-32-9-2	101 Md Mendelevium (260) 260 2.8-9-32-9-2	102 No Nobelium (259) 259 2.8-9-32-9-2	103 Lr Lawrencium (262) 262 2.8-9-32-9-3

# 1.1 Semiconductor materials

**Table 1.1** | A portion of the periodic table

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

[illegible]

# 1.1 Semiconductor materials

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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

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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

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1.1 Semiconductor materials

**1.2 Type of Solids**

1.3 Space lattices

1.4 The diamond structure

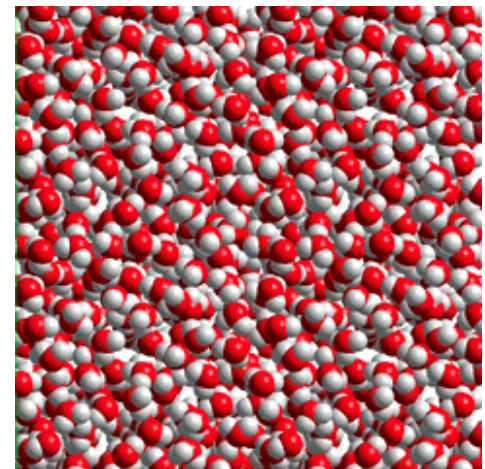
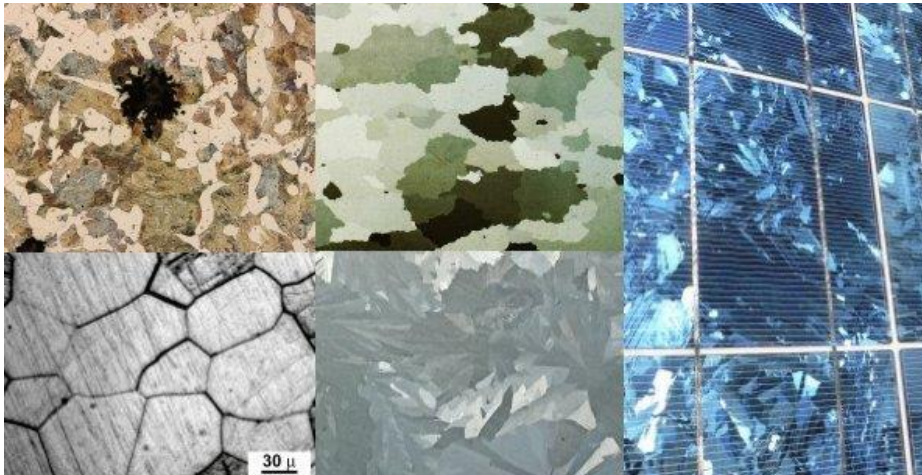
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

# 1.2 Type of Solids

## Solids:

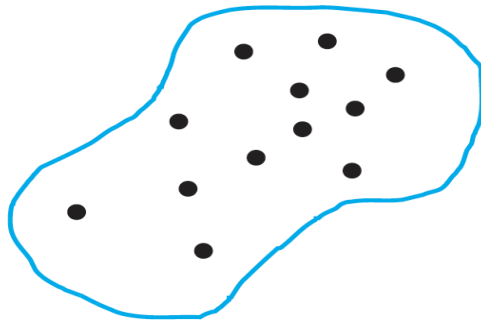
- Single crystals
- Polycrystals
- Amorphous



# 1.2 Type of Solids

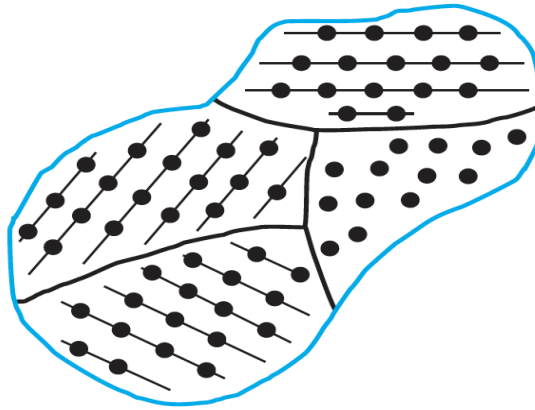
## Solids :

- Amorphous
- Polycrystals
- Single crystals



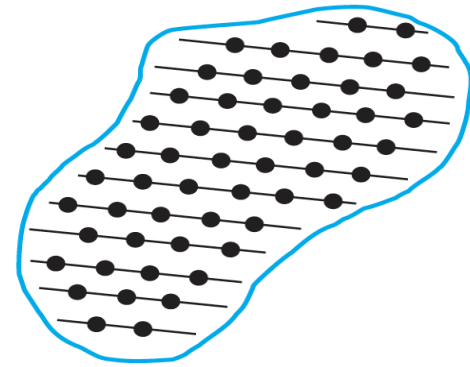
(a)

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 ( $\mu\text{m}$  scale)

# 1.2 Type of Solids

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## Characteristics of Crystals

- Specific shape and fixed melting point
- Atoms or ions periodically arranged in a relatively large scale ( $\mu\text{m}$ )

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

# Outline

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1.1 Semiconductor materials

1.2 Type of Solids

**1.3 Space lattices**

1.4 The diamond structure

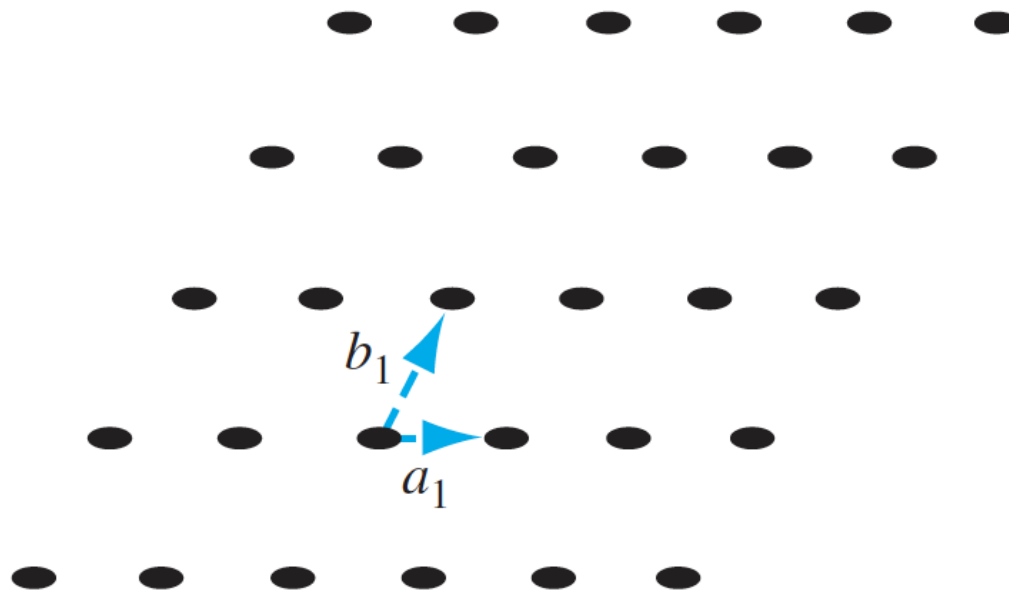
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

# 1.3 Space lattice

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## Primitive and Unit Cell

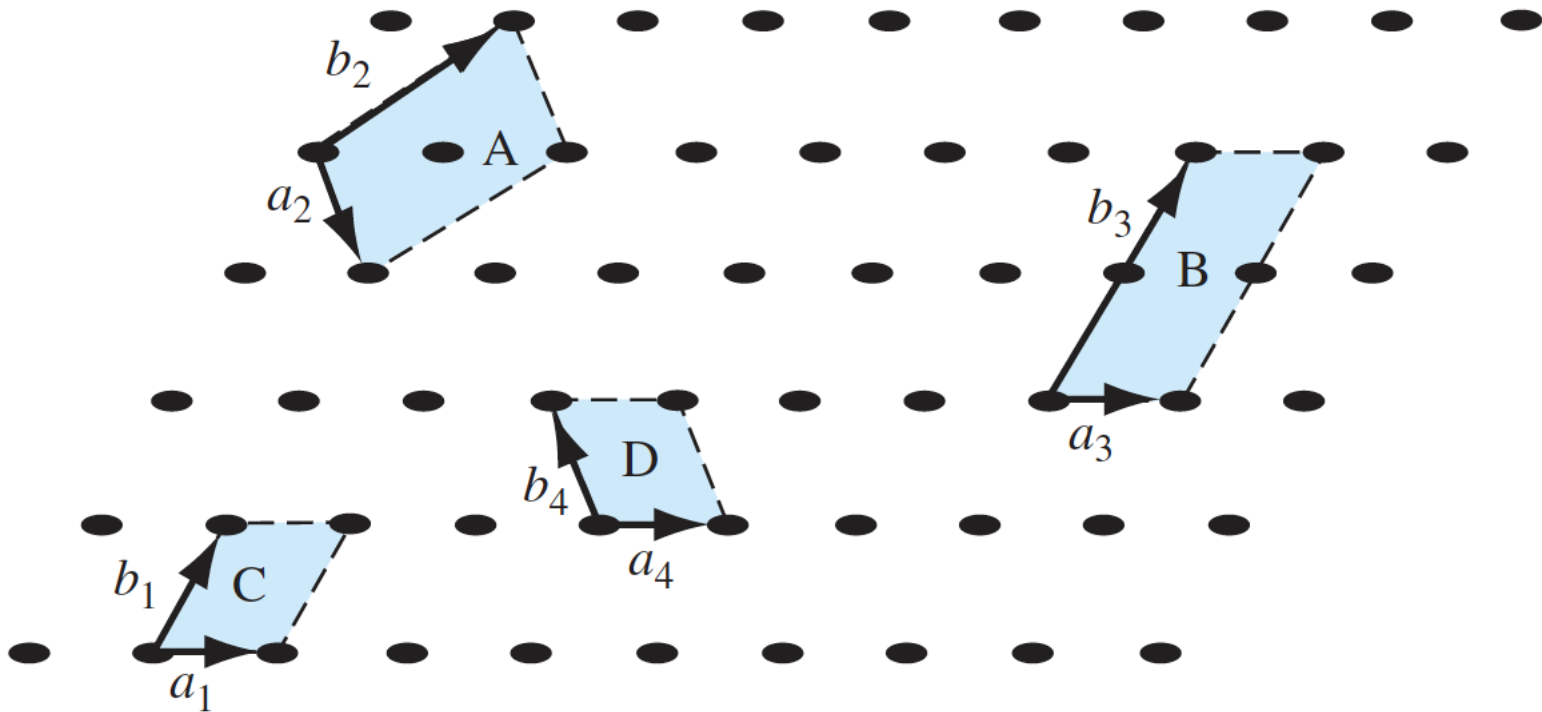


Unit cell: any small volume of crystal to reproduce the entire crystal.

Primitive cell: smallest unit cell

# 1.3 Space lattice

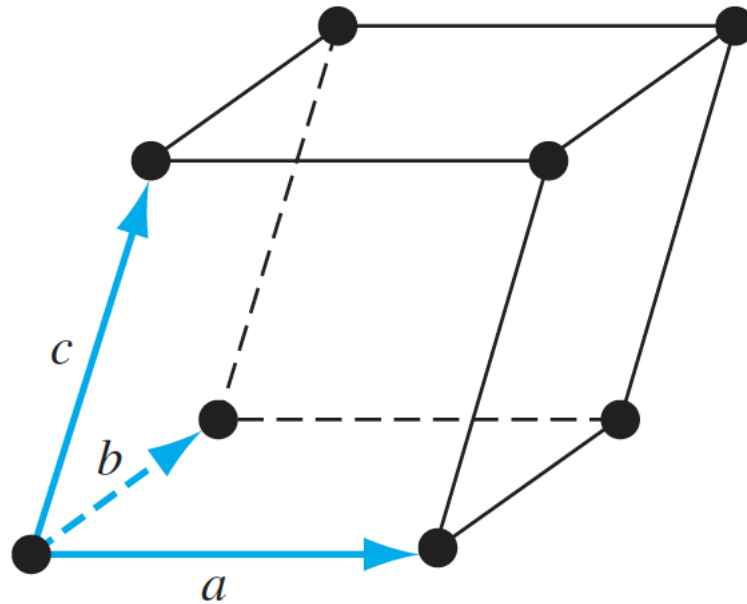
## Primitive and Unit Cell





# 1.3 Space lattice

## Primitive and Unit Cell

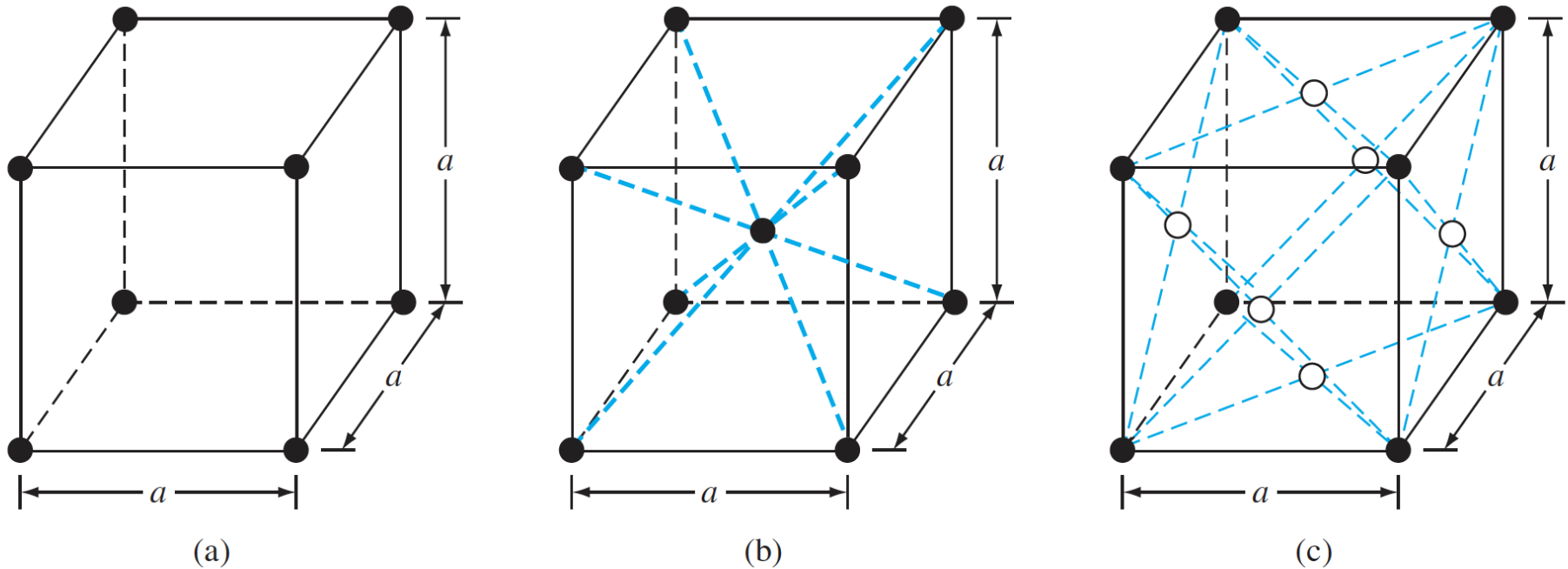


$$\vec{r} = p\vec{a} + q\vec{b} + s\vec{c}$$

A generalized primitive unit cell

# 1.3 Space lattice

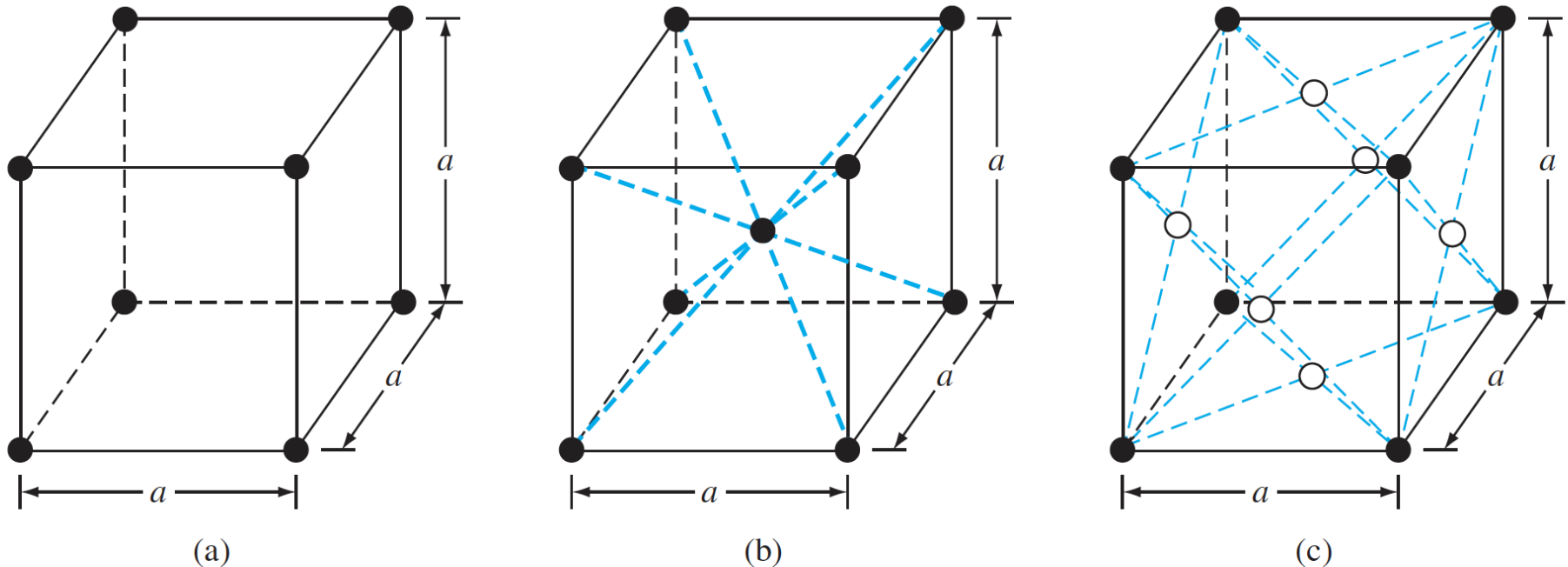
## Basic Crystal Structures



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

# 1.3 Space lattice

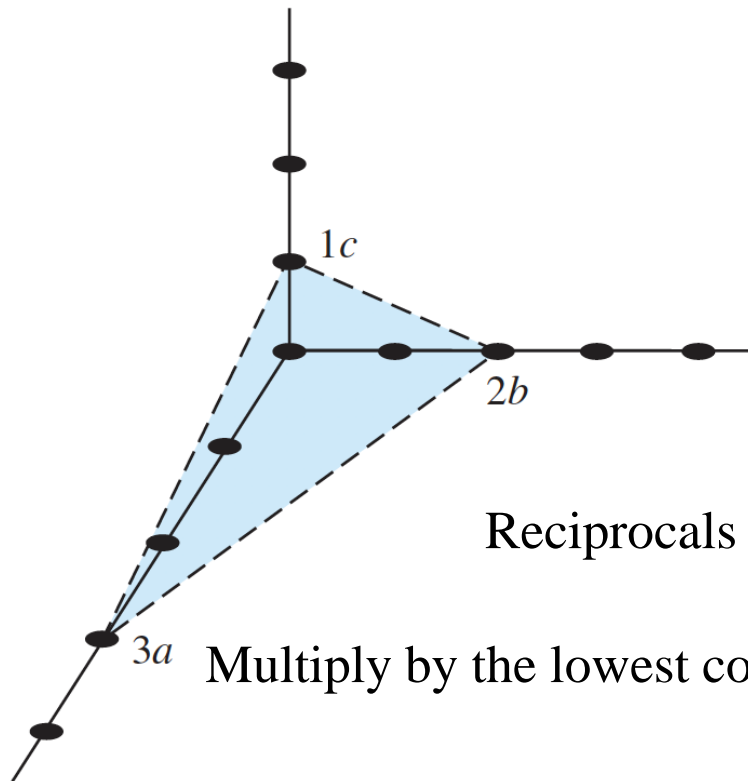
## Basic Crystal Structures: volume density of atoms



**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

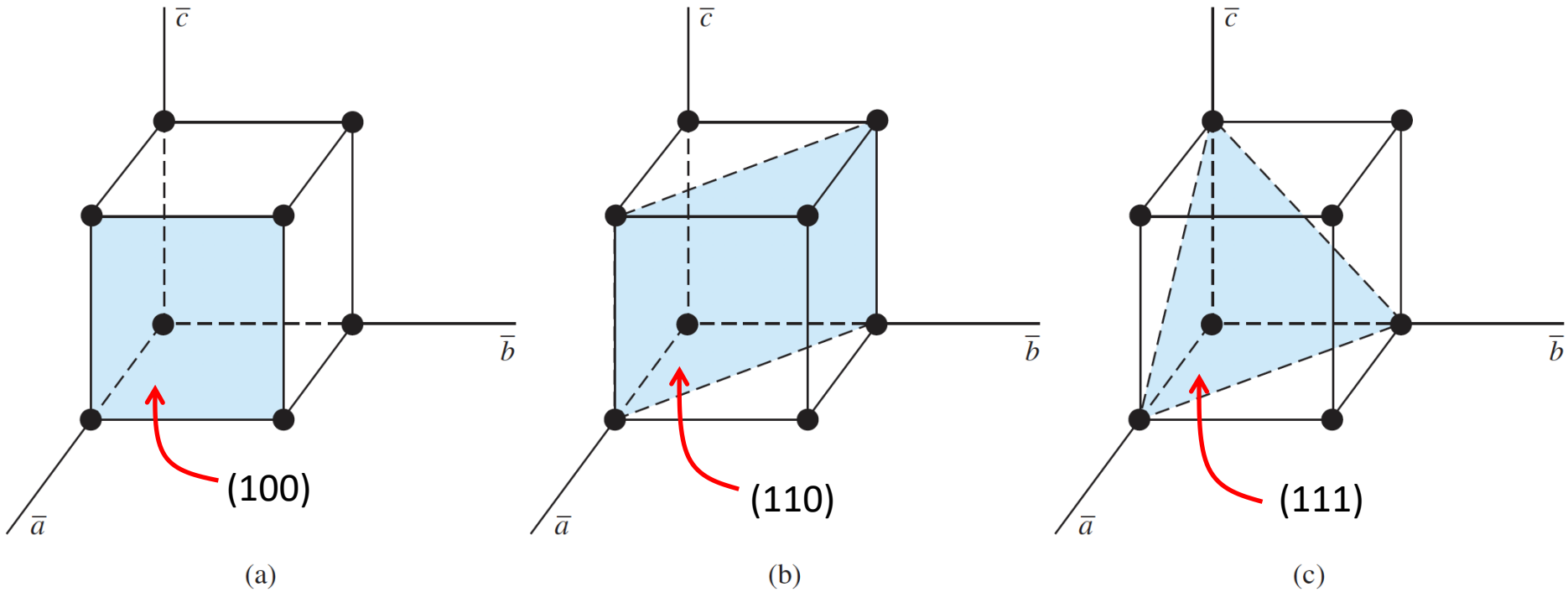


Reciprocals of the intercepts:  $(1/3, 1/2, 1)$

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

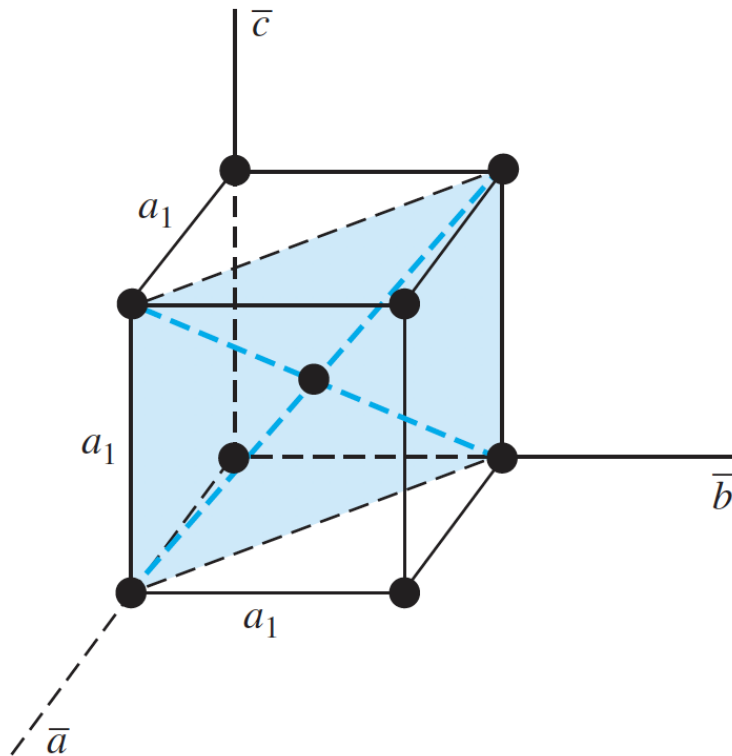
# 1.3 Space lattice

## Crystalline Plane and Miller Index

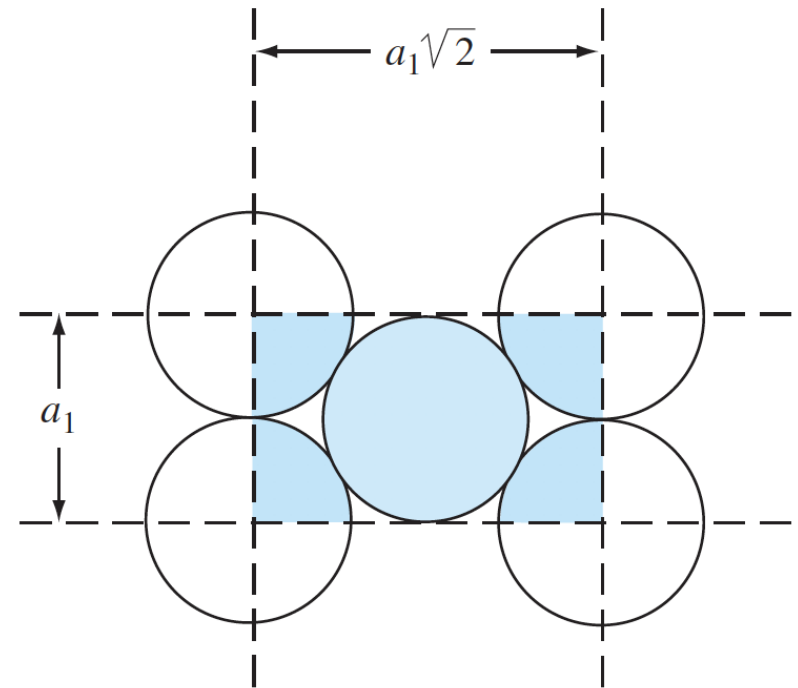


# 1.3 Space lattice

## Crystalline Plane and Miller Index: surface density of atoms



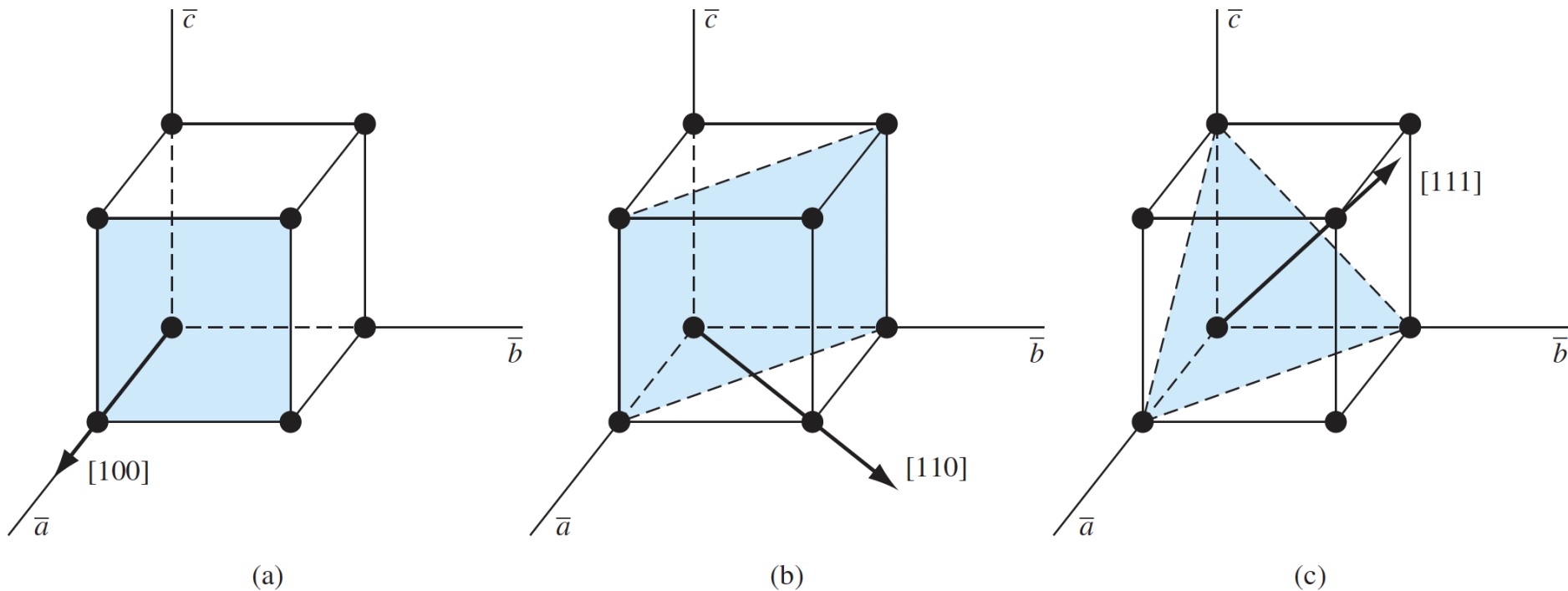
(a)



(b)

# 1.3 Space lattice

## Directions in Crystals



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

# Outline

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**1.4 The diamond structure**

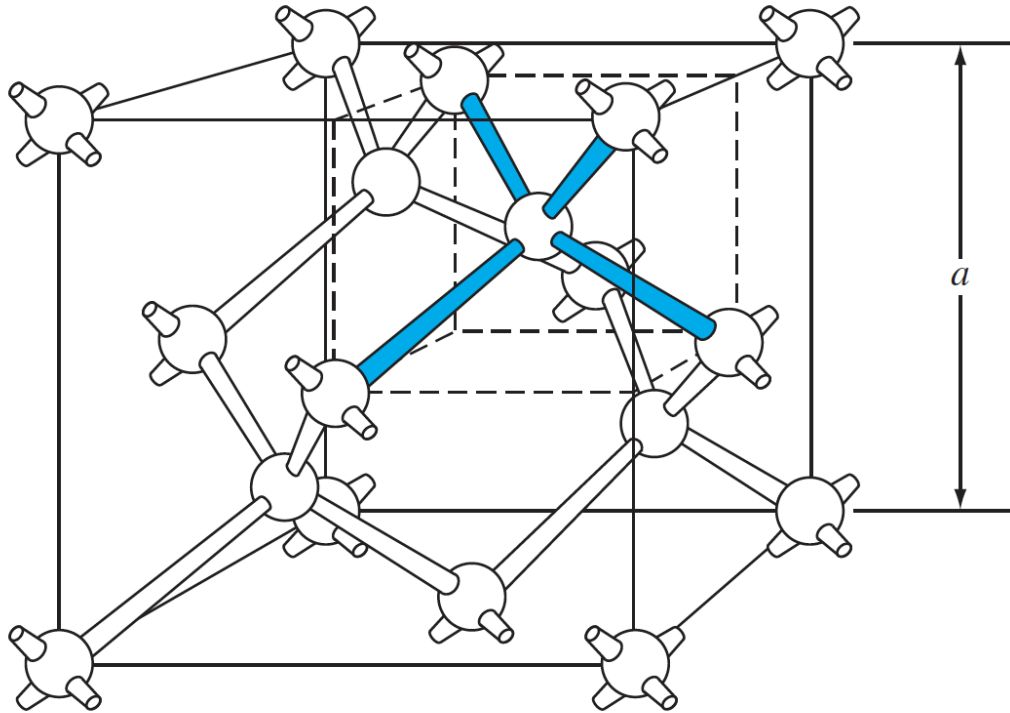
1.5 Atomic bonding

1.6 Imperfections and impurities in solids

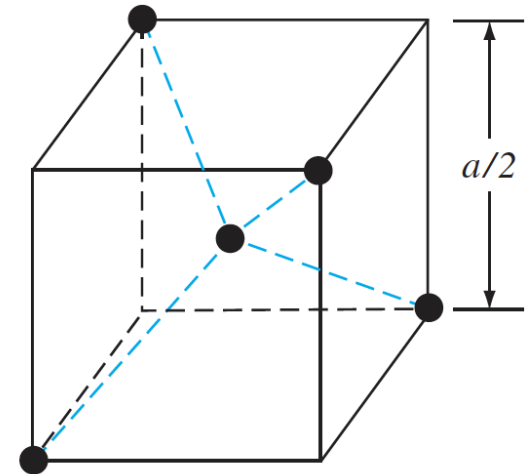


# 1.4 The diamond structure

## The diamond lattice



The diamond structure

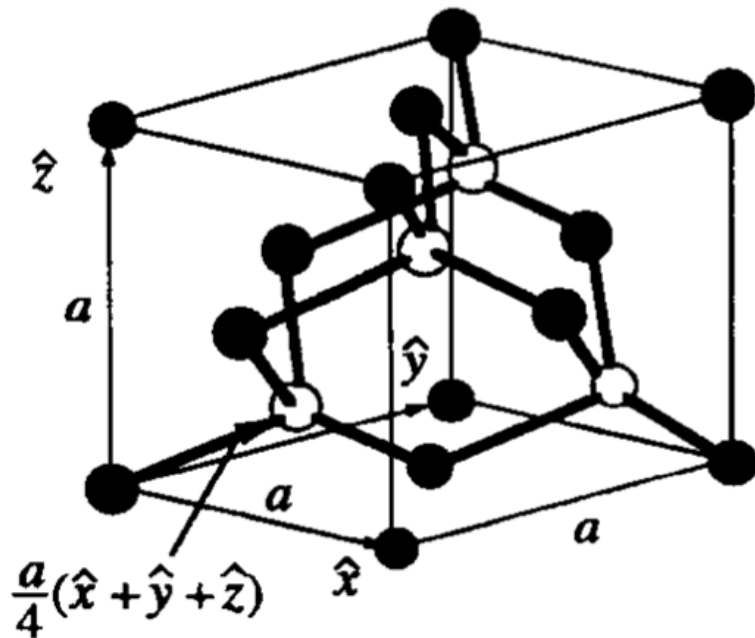


The tetrahedral structure of  
closest neighbors in the diamond  
lattice

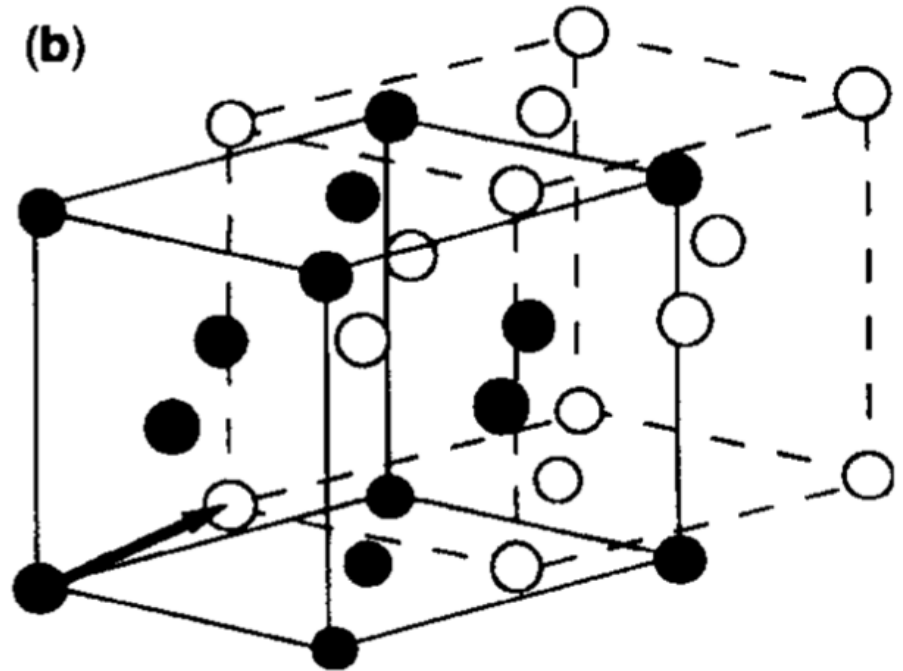
# 1.4 The diamond structure

## The diamond lattice

(a)



(b)

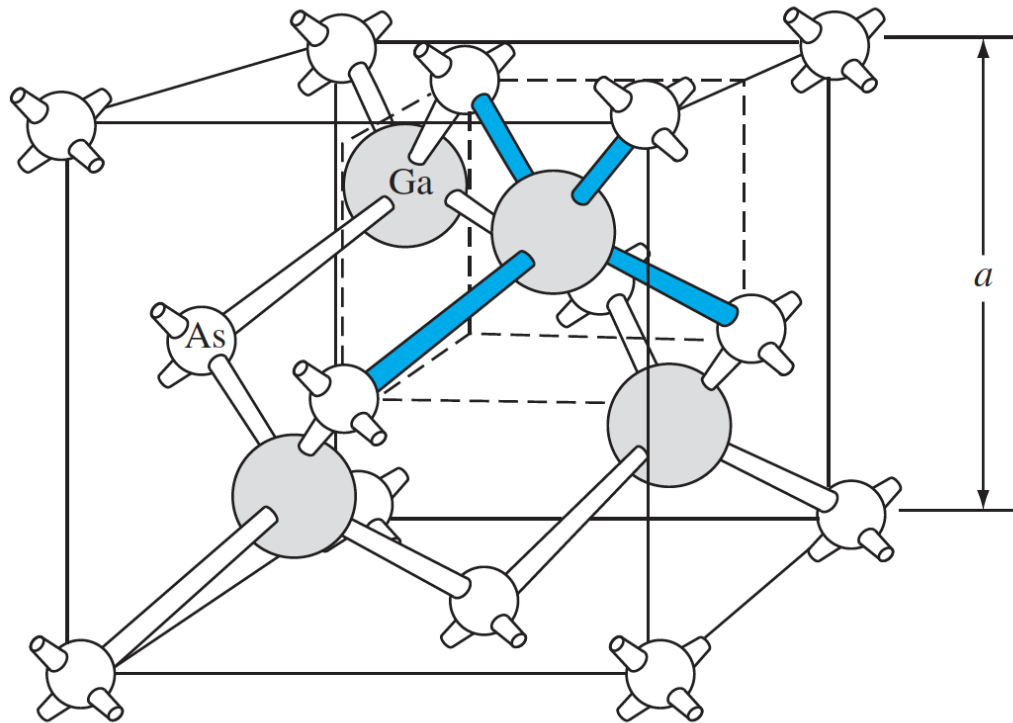


Equivalent to two face-centered cubics  
sliding  $\frac{1}{4}$  diagonal length along a diagonal

# 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

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1.1 Semiconductor materials

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1.4 The diamond structure

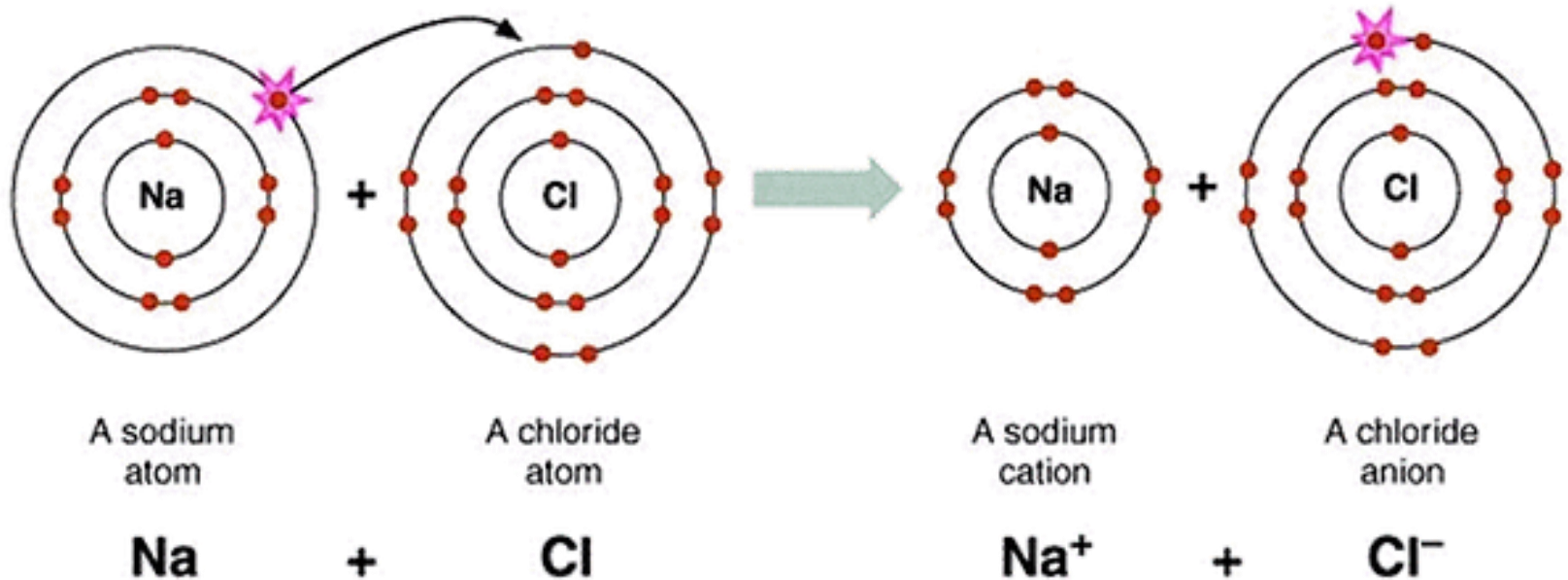
**1.5 Atomic bonding**

1.6 Imperfections and impurities in solids

# 1.5 Chemical bonds

Chemical Bonds: Binding of atoms or ions

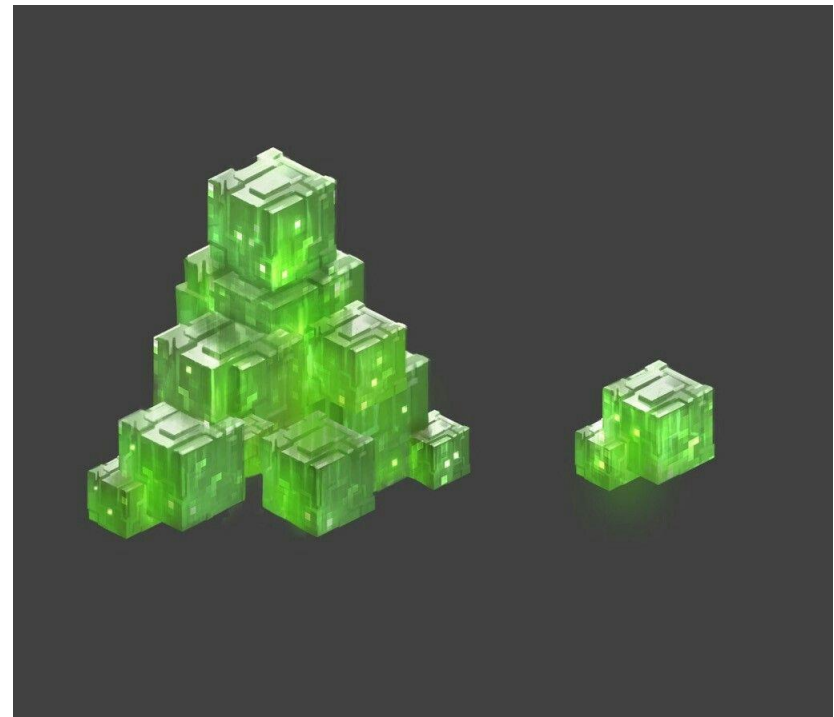
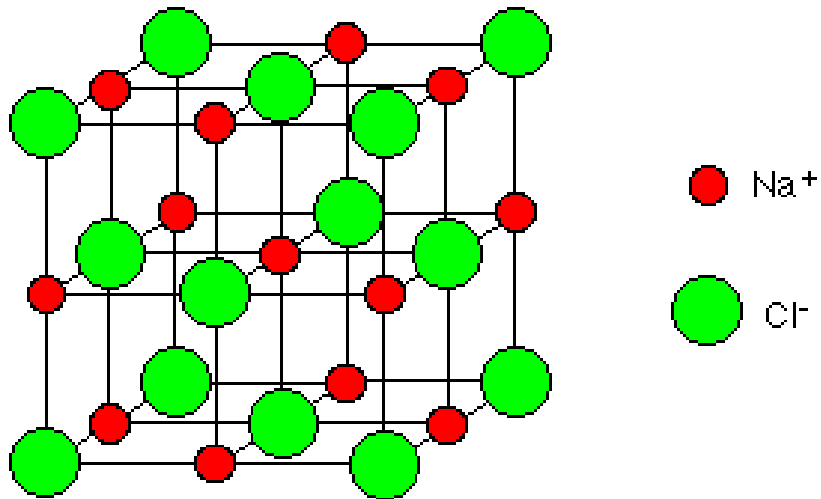
Ion bonds, metal bonds, covalent bonds



Ion bonds

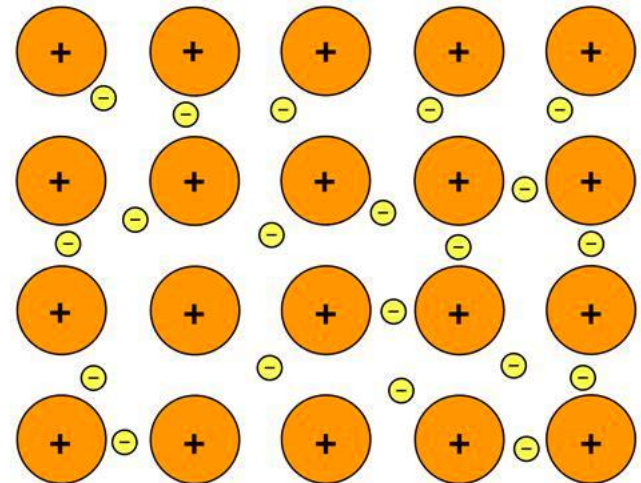
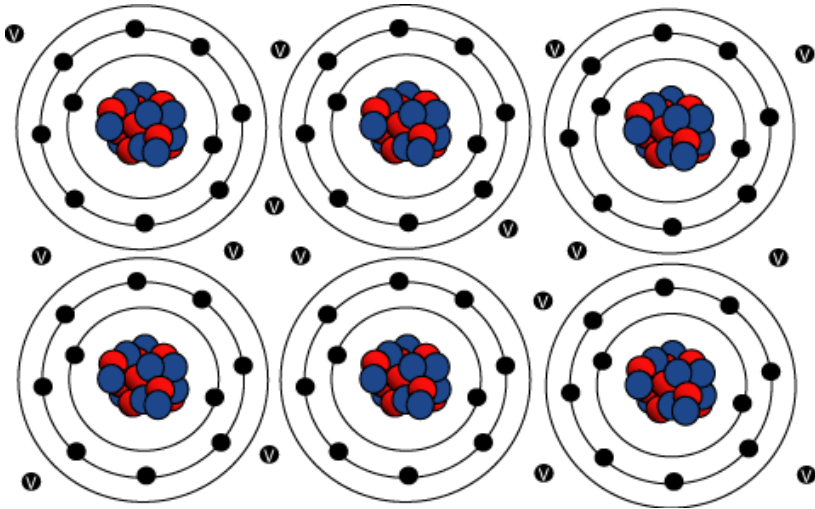
# 1.5 Chemical bonds

## Ion Crystals



# 1.5 Chemical bonds

## Metal bonds





# 1.5 Chemical bonds

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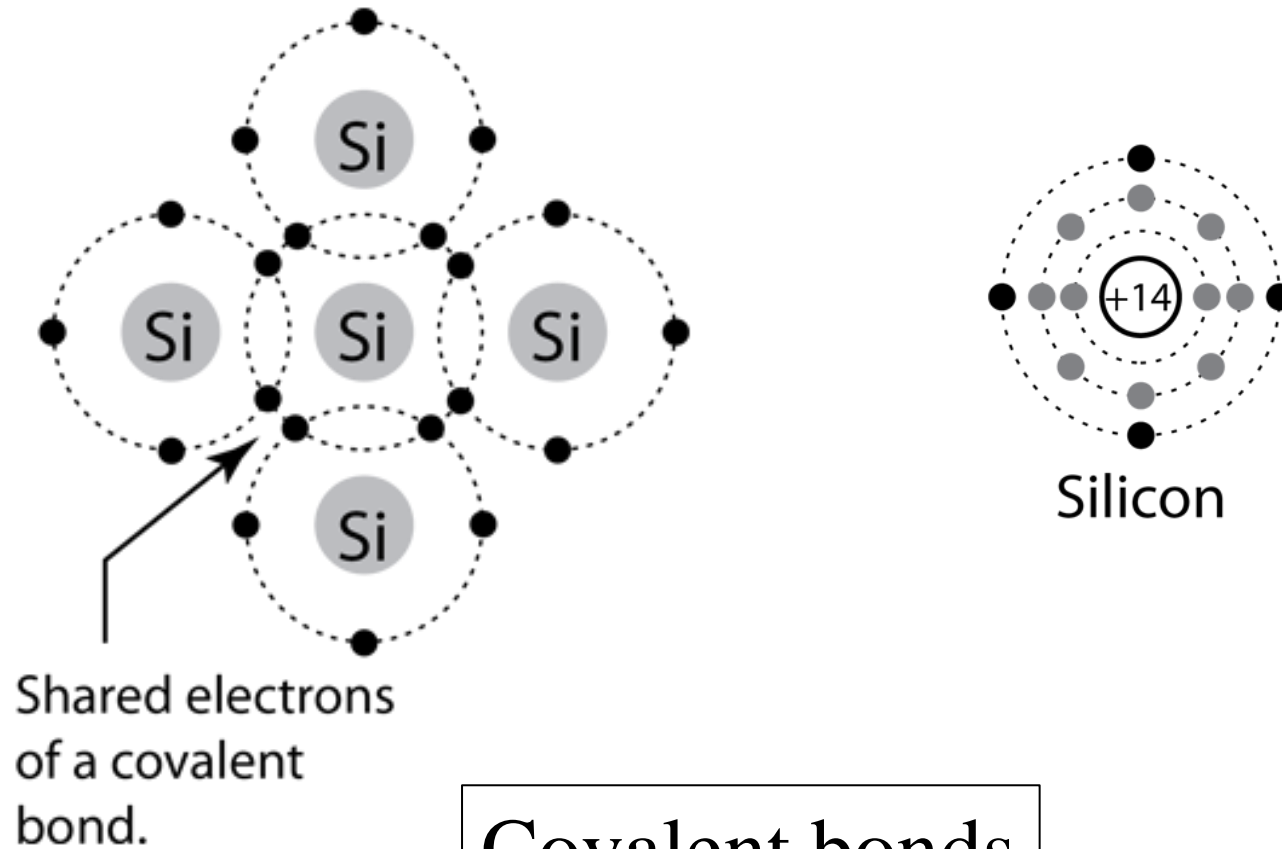
## Metal Crystals





# 1.5 Chemical bonds

Covalent bonds: shared electrons in outer orbitals



Covalent bonds

# 1.5 Chemical bonds

## Periodic Table of the Elements

<div>Atomic Number →</div> <div>← Symbol</div> <div>Name →</div> <div>← Atomic Weight</div> <div>Electrons per shell →</div>																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
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# Outline

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1.1 Semiconductor materials

1.2 Type of Solids

1.3 Space lattices

1.4 The diamond structure

1.5 Atomic bonding

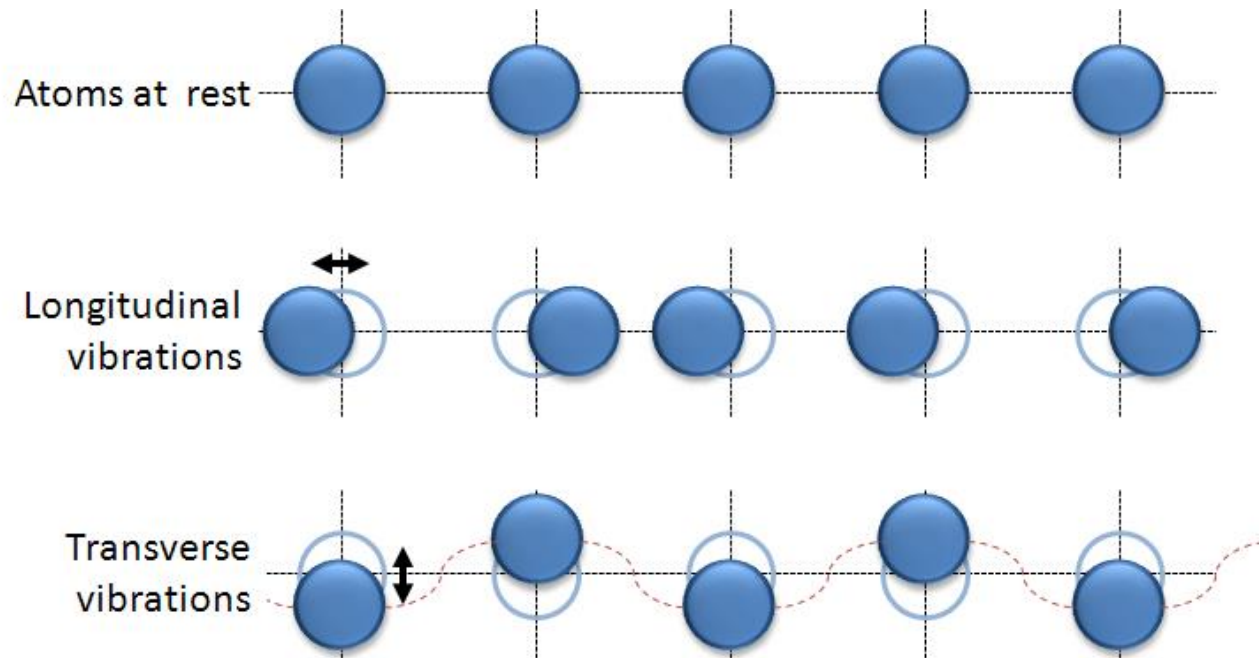
**1.6 Imperfections and impurities in solids**

# 1.6 Imperfections and impurities in solids

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## Imperfections in solids

Lattice vibrations: thermal vibration or phonons



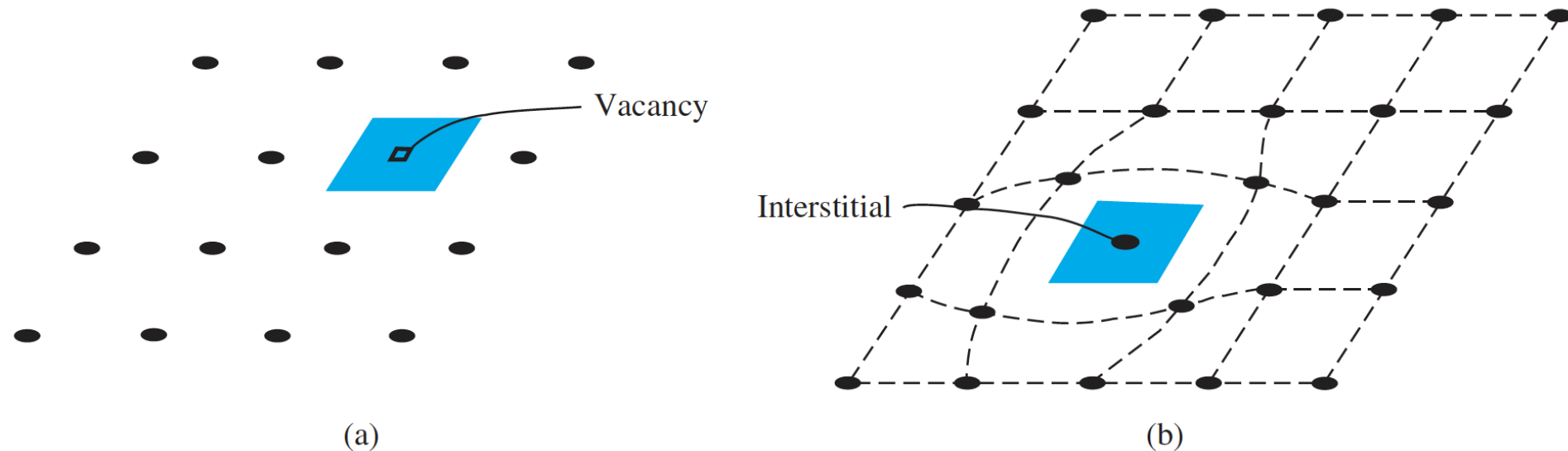
# 1.6 Imperfections and impurities in solids

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## Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

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



# 1.6 Imperfections and impurities in solids

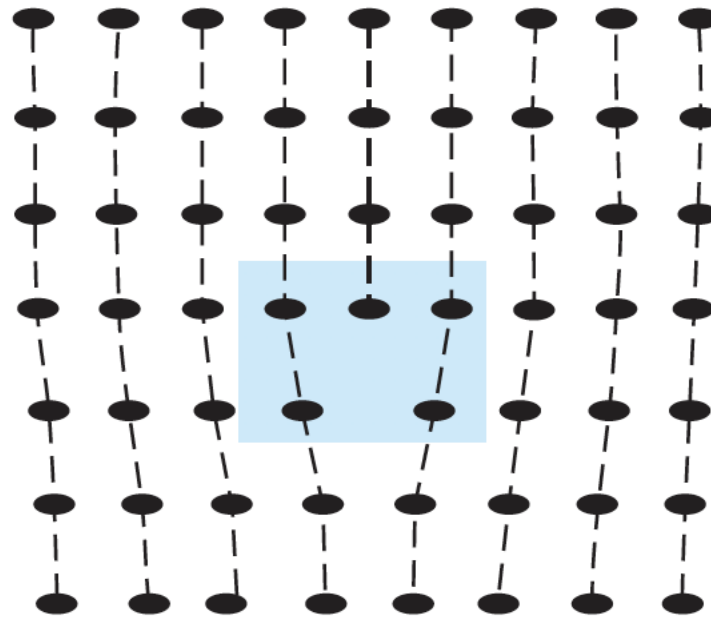
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## Imperfections in solids

Lattice vibrations: thermal vibration, or phonons

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

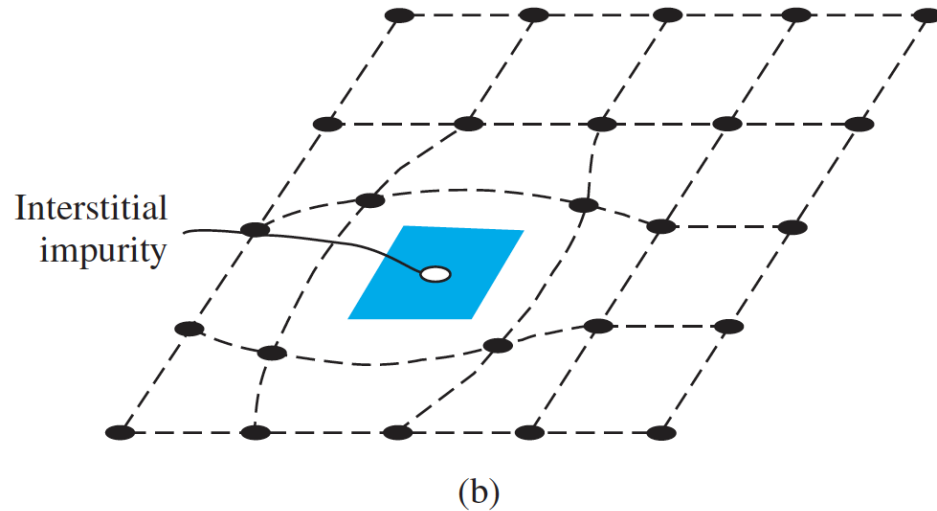
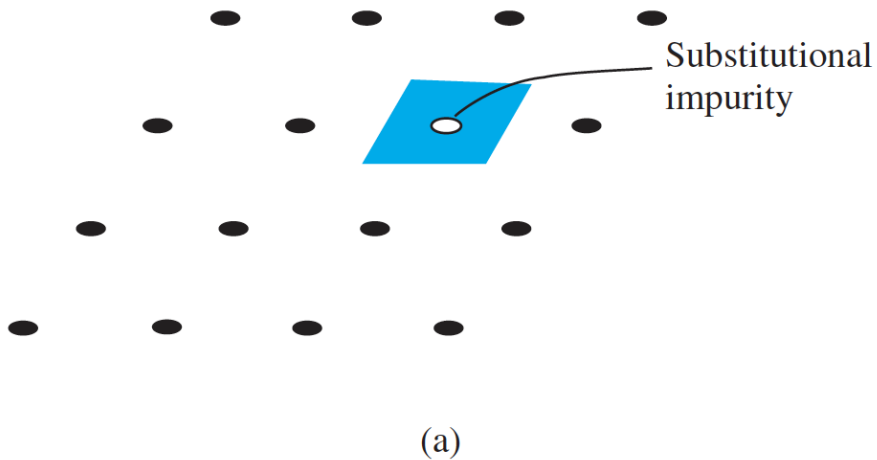
Line defects: line dislocation



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

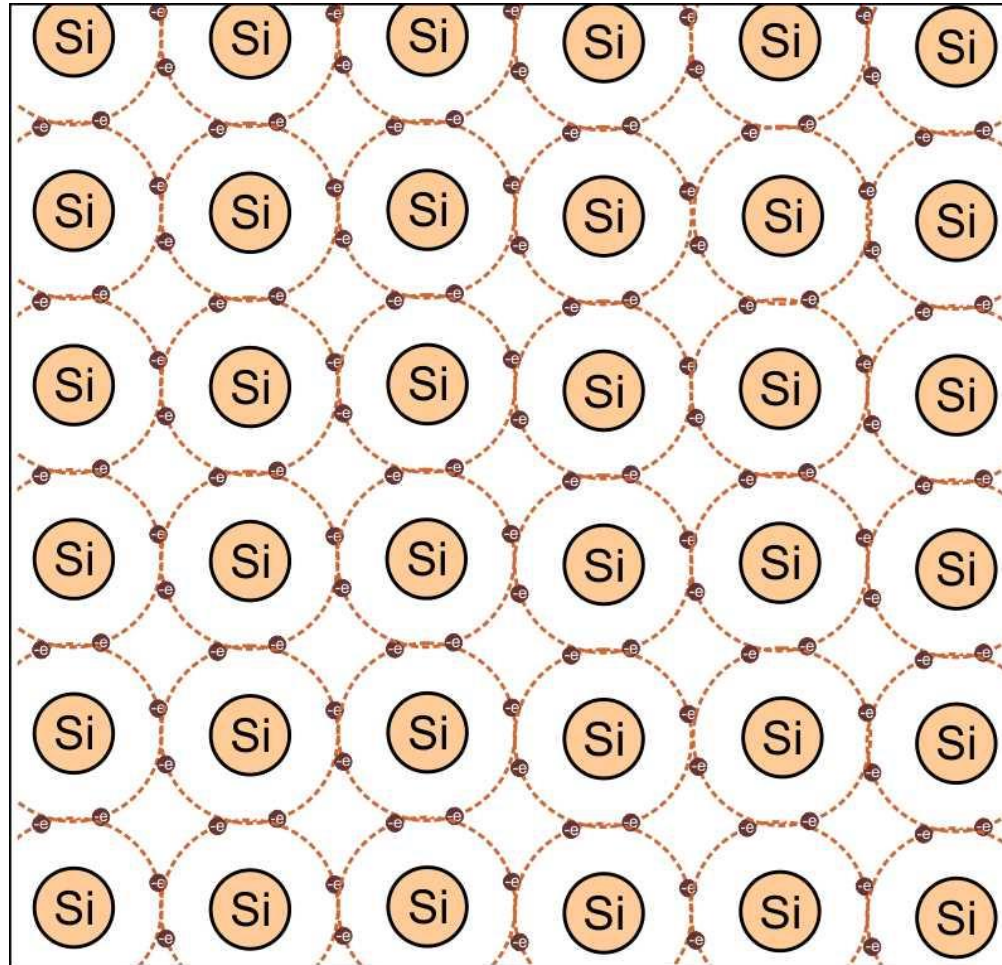
## Impurities in solids: foreign atoms

### Periodic Table of the Elements

<div>1 IA <b>H</b> Hydrogen 1.008</div>																		<div>2 IIA <b>He</b> Helium 4.0026</div>																		<div>3 IIIB <b>Sc</b> Scandium 44.955908</div>																		<div>4 IVB <b>Ti</b> Titanium 47.867</div>																		<div>5 VB <b>V</b> Vanadium 50.9415</div>																		<div>6 VIB <b>Cr</b> Chromium 51.9961</div>																		<div>7 VIIB <b>Mn</b> Manganese 54.938044</div>																		<div>8 VIIIB <b>Fe</b> Iron 55.845</div>																		<div>9 VIIIB <b>Co</b> Cobalt 58.933</div>																		<div>10 VIIIB <b>Ni</b> Nickel 58.693</div>																		<div>11 IB <b>Cu</b> Copper 63.546</div>																		<div>12 IIB <b>Zn</b> Zinc 65.38</div>																		<div>13 IIIA <b>Al</b> Aluminum 26.981</div>																		<div>14 IVA <b>Si</b> Silicon 28.085</div>																		<div>15 VA <b>P</b> Phosphorus 30.974</div>																		<div>16 VIA <b>S</b> Sulfur 32.06</div>																		<div>17 VIIA <b>Cl</b> Chlorine 35.45</div>																		<div>18 VIIA <b>Ar</b> Argon 39.948</div>																		<div>19 IIIB <b>K</b> Potassium 39.0983</div>																		<div>20 IVB <b>Ca</b> Calcium 40.078</div>																		<div>21 IIIB <b>Sc</b> Scandium 44.955908</div>																		<div>22 IVB <b>Ti</b> Titanium 47.867</div>																		<div>23 VB <b>V</b> Vanadium 50.9415</div>																		<div>24 VIB <b>Cr</b> Chromium 51.9961</div>																		<div>25 VIIB <b>Mn</b> Manganese 54.938044</div>																		<div>26 VIIIB <b>Fe</b> Iron 55.845</div>																		<div>27 VIIIB <b>Co</b> Cobalt 58.933</div>																		<div>28 VIIIB <b>Ni</b> Nickel 58.693</div>																		<div>29 IB <b>Cu</b> Copper 63.546</div>																		<div>30 IIB <b>Zn</b> Zinc 65.38</div>																		<div>31 IIIA <b>Ga</b> Gallium 69.723</div>																		<div>32 IVA <b>Ge</b> Germanium 72.630</div>																		<div>33 VA <b>As</b> Arsenic 74.921</div>																		<div>34 VIA <b>Se</b> Selenium 78.971</div>																		<div>35 VIIA <b>Br</b> Bromine 79.904</div>																		<div>36 VIIA <b>Kr</b> Krypton 83.798</div>																		<div>37 IIIB <b>Rb</b> Rubidium 85.4678</div>																		<div>38 IVB <b>Sr</b> Strontium 87.62</div>																		<div>39 IIIB <b>Y</b> Yttrium 88.90584</div>																		<div>40 IVB <b>Zr</b> Zirconium 91.224</div>																		<div>41 VB <b>Nb</b> Niobium 92.90637</div>																		<div>42 VIB <b>Mo</b> Molybdenum 95.94</div>																		<div>43 VIIB <b>Tc</b> Technetium (98)</div>																		<div>44 VIIIB <b>Ru</b> Ruthenium 101.07</div>																		<div>45 VIIIB <b>Rh</b> Rhodium 102.91</div>																		<div>46 VIIIB <b>Pd</b> Palladium 106.42</div>																		<div>47 IB <b>Ag</b> Silver 107.87</div>																		<div>48 IIB <b>Cd</b> Cadmium 112.41</div>																		<div>49 IIIA <b>In</b> Indium 114.82</div>																		<div>50 IVA <b>Sn</b> Tin 118.71</div>																		<div>51 VA <b>Sb</b> Antimony 121.76</div>																		<div>52 VIA <b>Te</b> Tellurium 127.60</div>																		<div>53 VIIA <b>I</b> Iodine 126.90</div>																		<div>54 VIIA <b>Xe</b> Xenon 131.29</div>																		<div>55 IIIB <b>Cs</b> Cesium 132.90545196</div>																		<div>56 IVB <b>Ba</b> Barium 137.327</div>																		<div>57-71 Lanthanides</div>																		<div>72 IIIB <b>Hf</b> Hafnium 178.49</div>																		<div>73 IVB <b>Ta</b> Tantalum 180.94788</div>																		<div>74 VB <b>W</b> Tungsten 183.84</div>																		<div>75 VIIB <b>Re</b> Rhenium 186.21</div>																		<div>76 VIIIB <b>Os</b> Osmium 190.23</div>																		<div>77 VIIIB <b>Ir</b> Iridium 192.22</div>																		<div>78 VIIIB <b>Pt</b> Platinum 195.08</div>																		<div>79 IB <b>Au</b> Gold 196.97</div>																		<div>80 IIB <b>Hg</b> Mercury 200.59</div>																		<div>81 IIIA <b>Tl</b> Thallium 204.38</div>																		<div>82 IVA <b>Pb</b> Lead 207.2</div>																		<div>83 VA <b>Bi</b> Bismuth 208.98</div>																		<div>84 VIA <b>Po</b> Polonium (209)</div>																		<div>85 VIIA <b>At</b> Astatine (210)</div>																		<div>86 VIIA <b>Rn</b> Radon (222)</div>																		<div>87 IIIB <b>Fr</b> Francium (223)</div>																		<div>88 IVB <b>Ra</b> Radium (226)</div>																		<div>89-103 Actinides</div>																		<div>104 IIIB <b>Rf</b> Rutherfordium (261)</div>																		<div>105 IVB <b>Db</b> Dubnium (268)</div>																		<div>106 VB <b>Sg</b> Seaborgium (266)</div>																		<div>107 VIIB <b>Bh</b> Bohrium (264)</div>																		<div>108 VIIIB <b>Hs</b> Hassium (277)</div>																		<div>109 VIIIB <b>Mt</b> Meitnerium (276)</div>																		<div>110 VIIIB <b>Ds</b> Darmstadtium (281)</div>																		<div>111 IB <b>Rg</b> Roentgenium (282)</div>																		<div>112 IIB <b>Cn</b> Copernicium (285)</div>																		<div>113 IIIA <b>Nh</b> Nihonium (284)</div>																		<div>114 IVA <b>Fl</b> Flerovium (289)</div>																		<div>115 VA <b>Mc</b> Moscovium (288)</div>																		<div>116 VIA <b>Lv</b> Livermorium (293)</div>																		<div>117 VIIA <b>Ts</b> Tennessine (294)</div>																		<div>118 VIIA <b>Og</b> Oganesson (294)</div>																		<div>57 IIIB <b>La</b> Lanthanum 138.91</div>																		<div>58 IVB <b>Ce</b> Cerium 140.12</div>																		<div>59 IIIB <b>Pr</b> Praseodymium 140.91</div>																		<div>60 IVB <b>Nd</b> Neodymium 144.24</div>																		<div>61 IIIB <b>Pm</b> Promethium (145)</div>																		<div>62 IVB <b>Sm</b> Samarium 150.36</div>																		<div>63 IIIB <b>Eu</b> Europium 151.96</div>																		<div>64 IVB <b>Gd</b> Gadolinium 157.25</div>																		<div>65 IIIB <b>Tb</b> Terbium 158.93</div>																		<div>66 IVB <b>Dy</b> Dysprosium 162.50</div>																		<div>67 IIIB <b>Ho</b> Holmium 164.93</div>																		<div>68 IVB <b>Er</b> Erbium 167.26</div>																		<div>69 IIIB <b>Tm</b> Thulium 168.93</div>																		<div>70 IVB <b>Yb</b> Ytterbium 173.05</div>																		<div>71 IIIB <b>Lu</b> Lutetium 174.967</div>																		<div>89 IIIB <b>Ac</b> Actinium (227)</div>																		<div>90 IVB <b>Th</b> Thorium 232.04</div>																		<div>91 IIIB <b>Pa</b> Protactinium 231.04</div>																		<div>92 IVB <b>U</b> Uranium 238.03</div>																		<div>93 IIIB <b>Np</b> Neptunium (237)</div>																		<div>94 IVB <b>Pu</b> Plutonium (244)</div>																		<div>95 IIIB <b>Am</b> Americium (243)</div>																		<div>96 IVB <b>Cm</b> Curium (247)</div>																		<div>97 IIIB <b>Bk</b> Berkelium (247)</div>																		<div>98 IVB <b>Cf</b> Californium (251)</div>																		<div>99 IIIB <b>Es</b> Einsteinium (252)</div>																		<div>100 IVB <b>Fm</b> Fermium (257)</div>																		<div>101 IIIB <b>Md</b> Mendelevium (258)</div>																		<div>102 IVB <b>No</b> Nobelium (259)</div>																		<div>103 IIIB <b>Lr</b> Lawrencium (260)</div>																	
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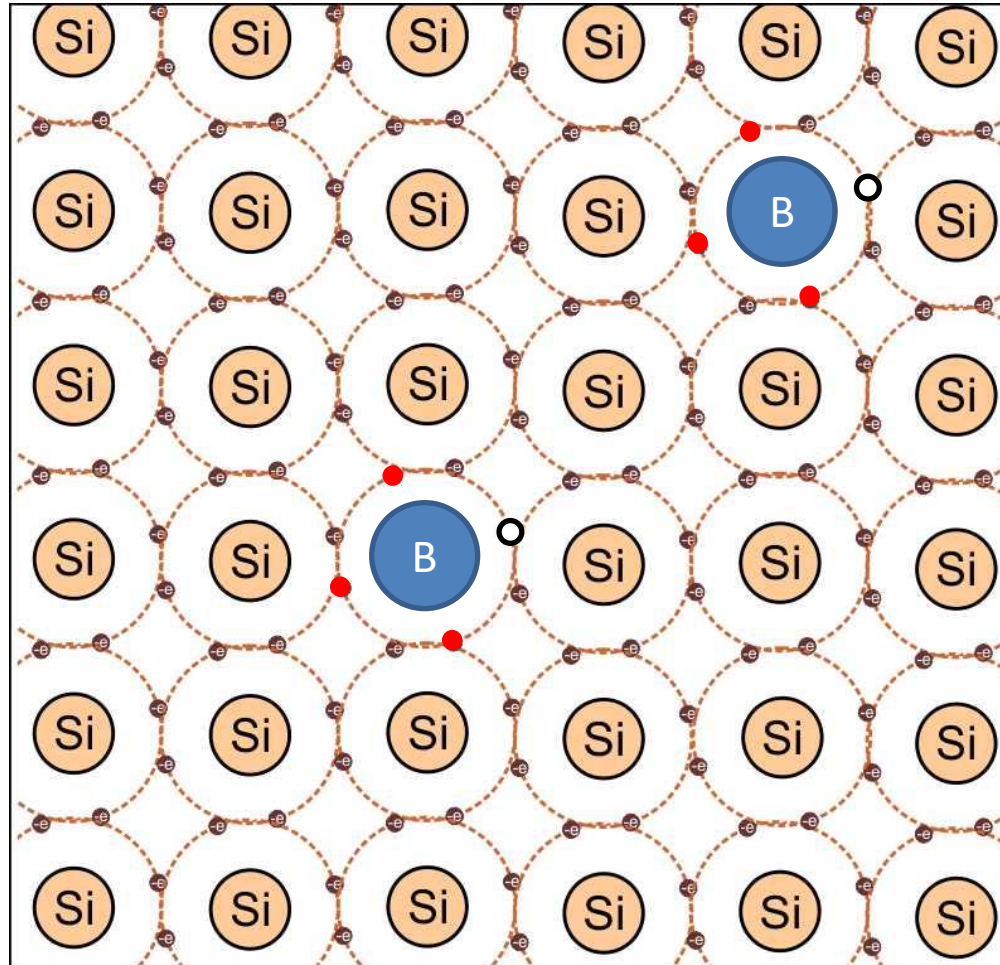


# 1.6 Imperfections and impurities in solids



# 1.6 Imperfections and impurities in solids

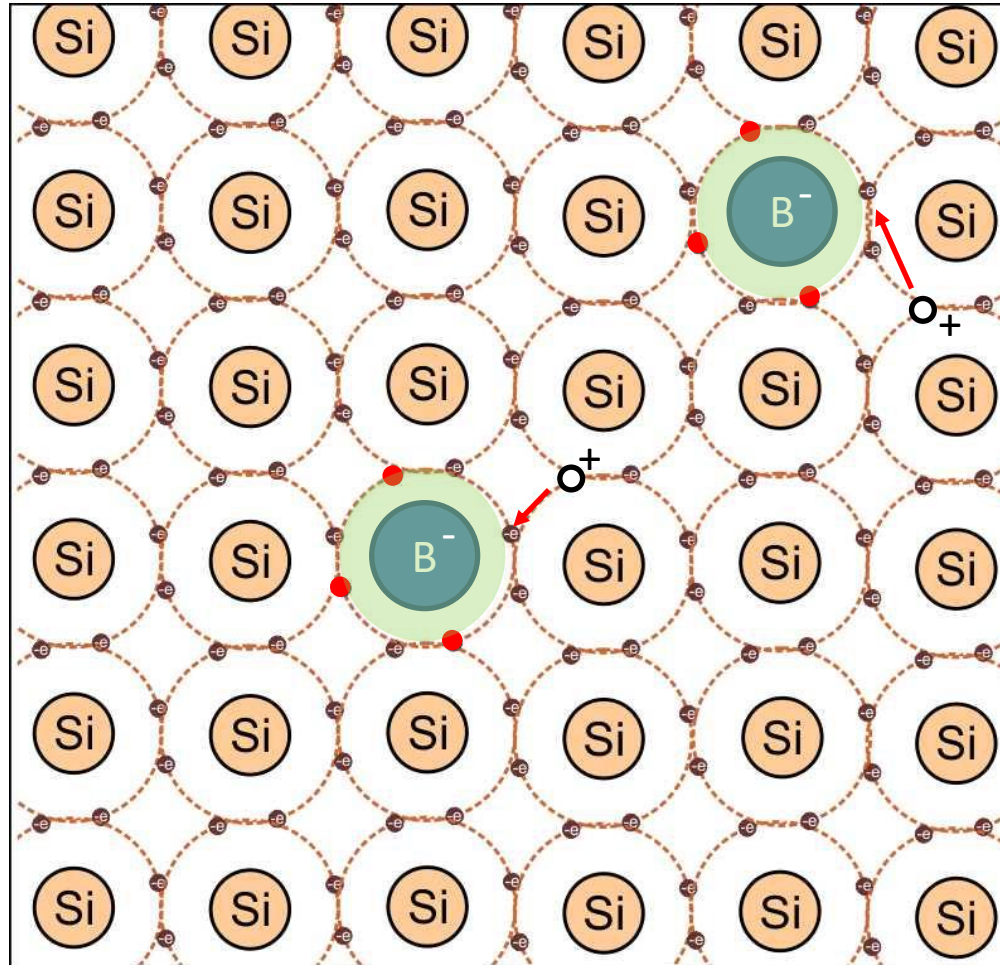
p-type  
doping



Acceptor-type of doping

# 1.6 Imperfections and impurities in solids

p-type  
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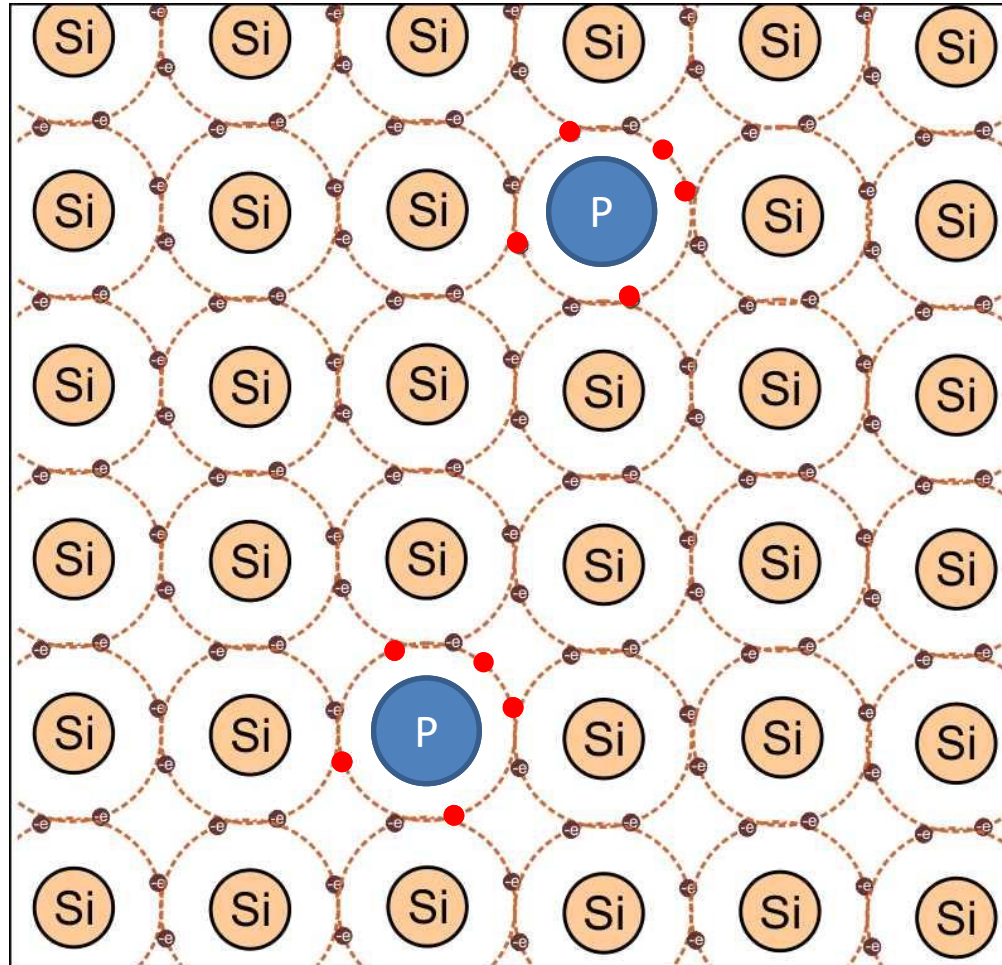


Acceptor-type of doping



# 1.6 Imperfections and impurities in solids

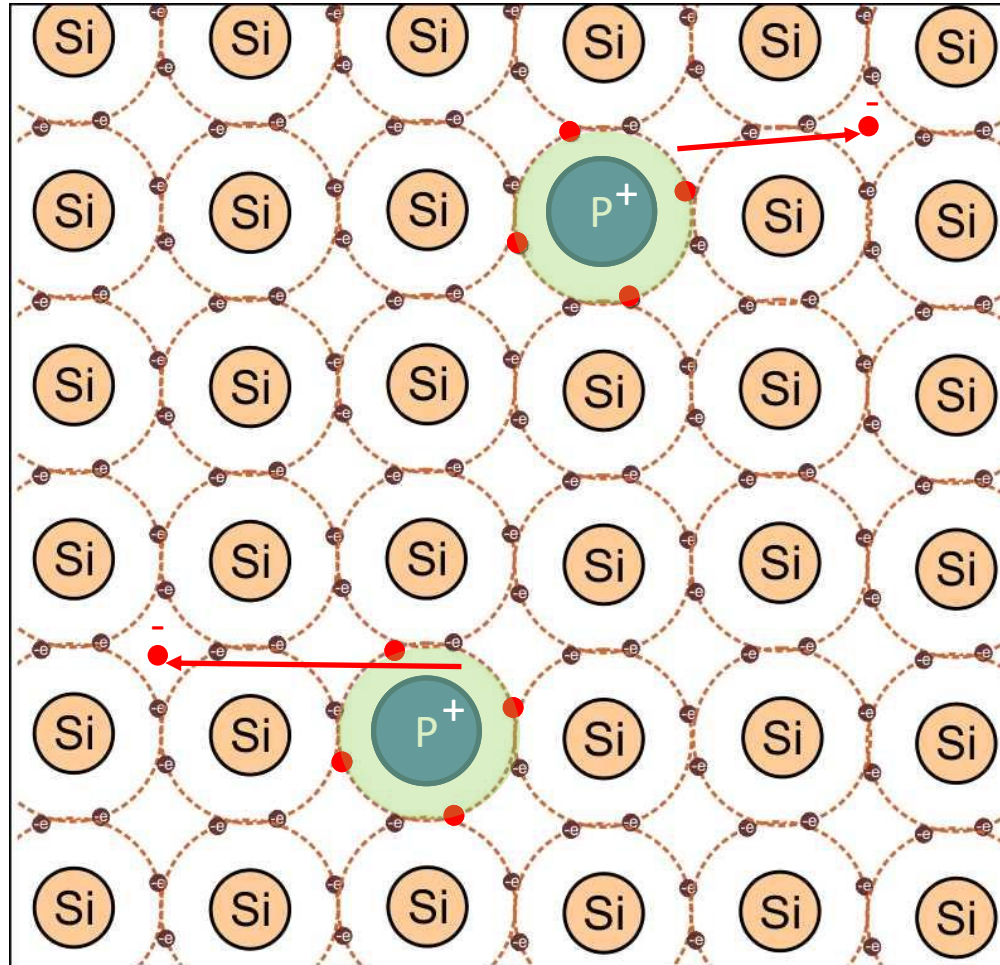
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Donor-type of doping

# 1.6 Imperfections and impurities in solids

n-type  
doping



Donor-type of doping