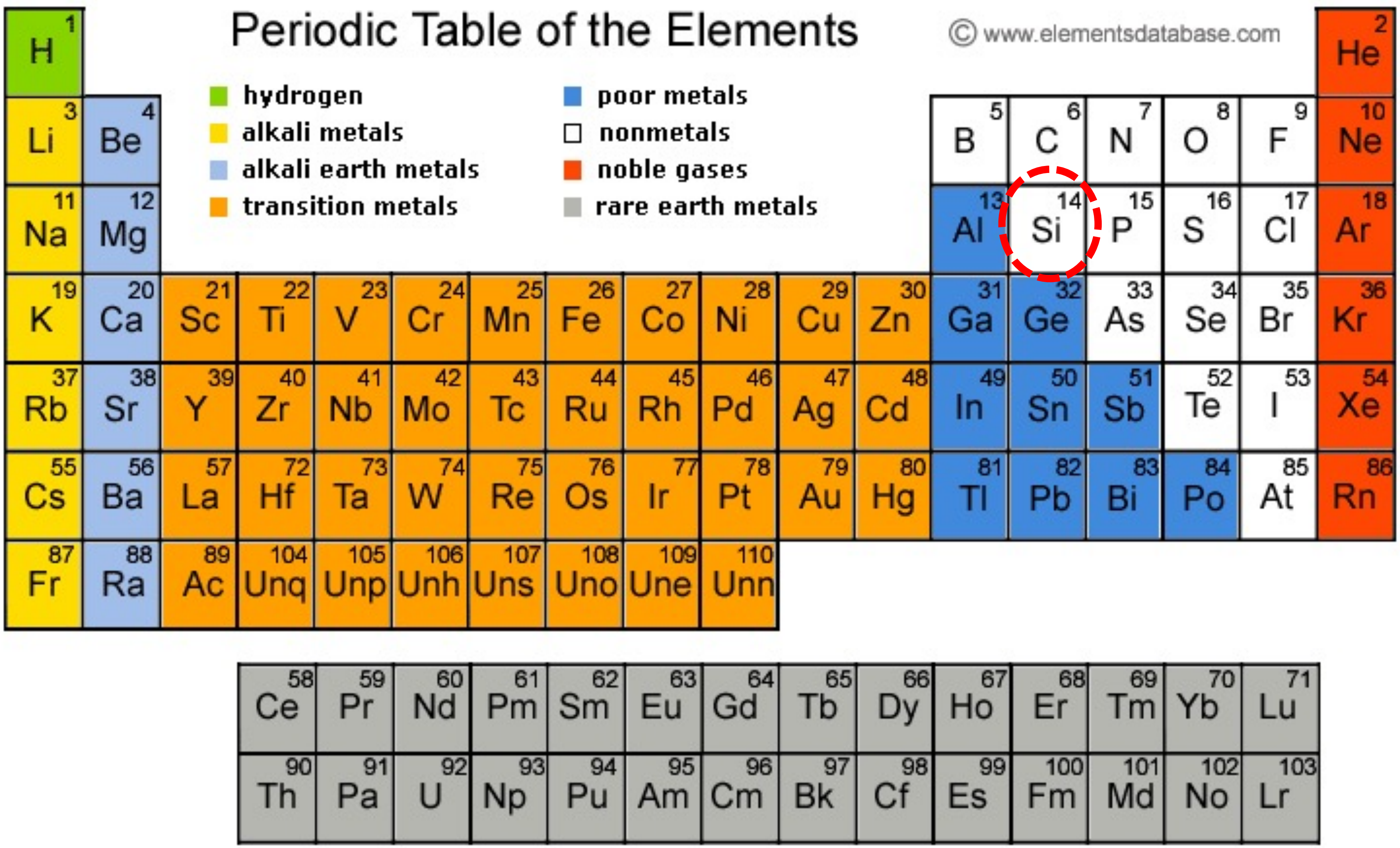
Lecture 2

1 INTRODUCTION TO SEMICONDUCTOR

1.1 Electronic configuration of atoms

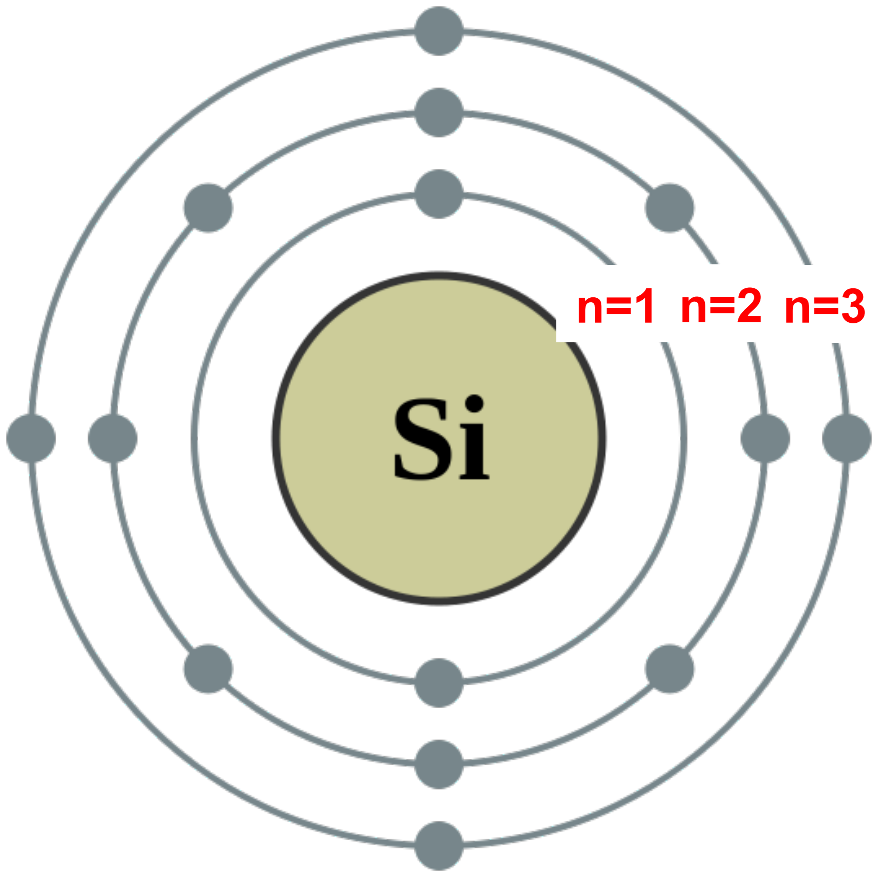
- Table 1.1 is the periodic table of the elements.
- The construction of electronic configuration in atoms is discussed in Appendix A (*advanced topic, not required in exam*).
- The electronic configurations of some common elements in semiconductors are given.

Table 1.1 Periodic table of elements



- The understanding and knowledge of electronic configurations of atoms are required to understand, for example:
  - the atomic bonding in semiconductors (discussed in section 1.2);
  - the construction of energy band diagram (discussed in Chapter 3);
  - the behavior of impurity/dopant atoms in semiconductors (discussed in Chapter 4);
  - and many other things…

Electronic configuration of silicon



https://commons.wikimedia.org/wiki/File:Electron_shell_014_Silicon_-_no_label.svg

Available quantum states in atoms

n	Subshell	No. of states	Max. No. of electrons
1	*s*	2 (2x1)	2
2	*s*	2 (2x1)	2
	p	6 (2x3)	6
3	*s*	2 (2x1)	2
	p	6 (2x3)	6
	d	10 (2x5)	10

How about n = 4?

n	Subshell	No. of states	Max. No. of electrons
4	*s*		
	p		
	d		

Atom	1*s*	2*s*	2*p*			Electron Configuration
Li	↑↓	↑				$1s^2 2s^1$
Be	↑↓	↑↓				$1s^2 2s^2$
B	↑↓	↑↓	↑			$1s^2 2s^2 2p^1$
C	↑↓	↑↓	↑	↑		$1s^2 2s^2 2p^2$
N	↑↓	↑↓	↑	↑	↑	$1s^2 2s^2 2p^3$
O	↑↓	↑↓	↑↓	↑	↑	$1s^2 2s^2 2p^4$
F	↑↓	↑↓	↑↓	↑↓	↑	$1s^2 2s^2 2p^5$
Ne	↑↓	↑↓	↑↓	↑↓	↑↓	$1s^2 2s^2 2p^6$

Table 1.2 Electronic configuration of some common elements in semiconductors

Element	Symbol	Atomic number	Electronic configuration
Boron	B	5	$1s^2\ 2s^2\ 2p^1$
Silicon	Si	14	$1s^2\ 2s^2\ 2p^6\ \underline{3s^2\ 3p^2}$
Phosphorus	P	15	
Gallium	Ga	31	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^1$
Germanium	Ge	32	
Arsenic	As	33	

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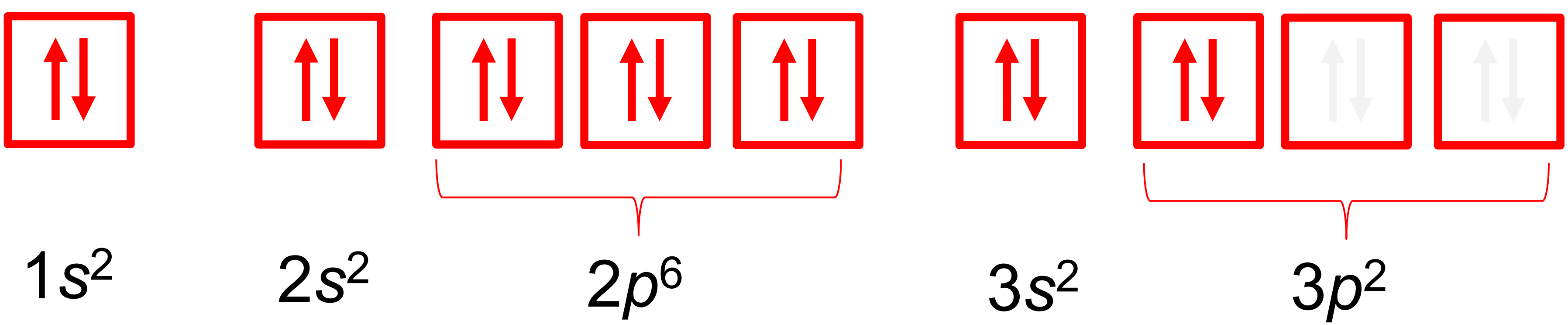
Gallium	Ga	31	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^1$
Germanium	Ge	32	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$
Arsenic	As	33	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^3$

1.2 Atomic bonding in semiconductor

- A solid can be conductor or dielectric depends on the types of bonds, or interaction, between its atoms.
- Solids are mostly formed by ionic, covalent and metallic bonds.
- Semiconductor materials (e.g. Si, Ge, GaAs….etc.) have covalent bonds.
- Covalent bond:
  - formed by sharing the electrons between atoms so that the atoms achieve a stable electron configuration (i.e. complete subshells)

- Consider Si: $1s^2\ 2s^2\ 2p^6$ <u>$3s^2\ 3p^2$</u>
  - To have complete subshells each Si atoms needs four more electrons.
  - This is achieved by making bonds with four nearest neighbors of Si atoms, with each Si atom contribute one electron.
  - This is conveniently illustrated in 2-dimensional representation in Fig.1.1.



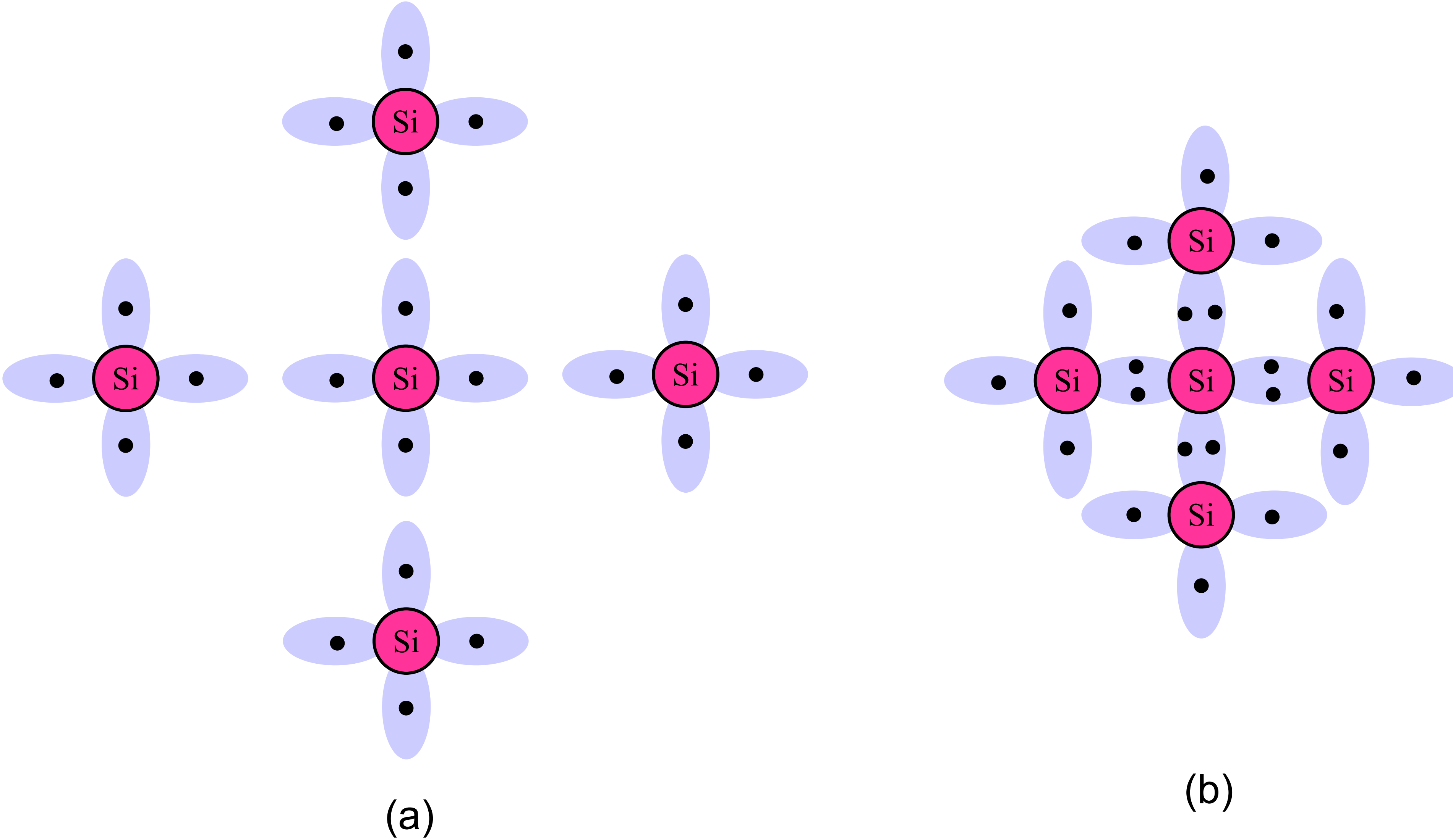
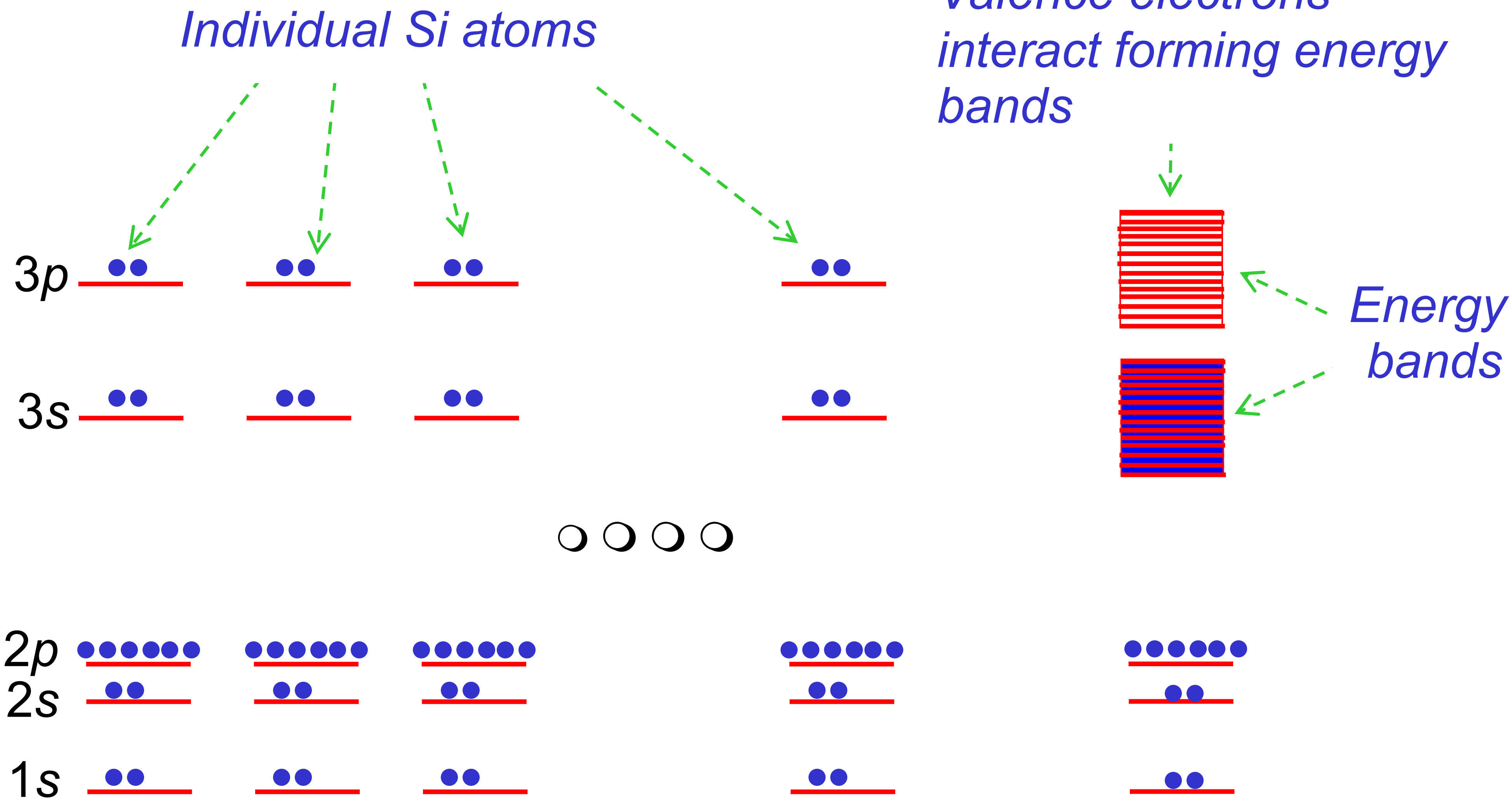


Fig. 1.1 Illustration of (a) silicon valence electrons (b) covalent bonding in the silicon crystal

$$\boxed{\text{Si} - 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2}$$



- When atoms are brought together, the interaction of valence electrons lead to the formation of an electron energy band (discussed in Chapter 3).

- The electrical properties of a solid are the consequence of the energy band structure:
  - The electrical conduction can only take place when there is empty states in the energy band.
  - Typical energy band diagrams of metals, semiconductors and insulators are shown in Fig. 1.2

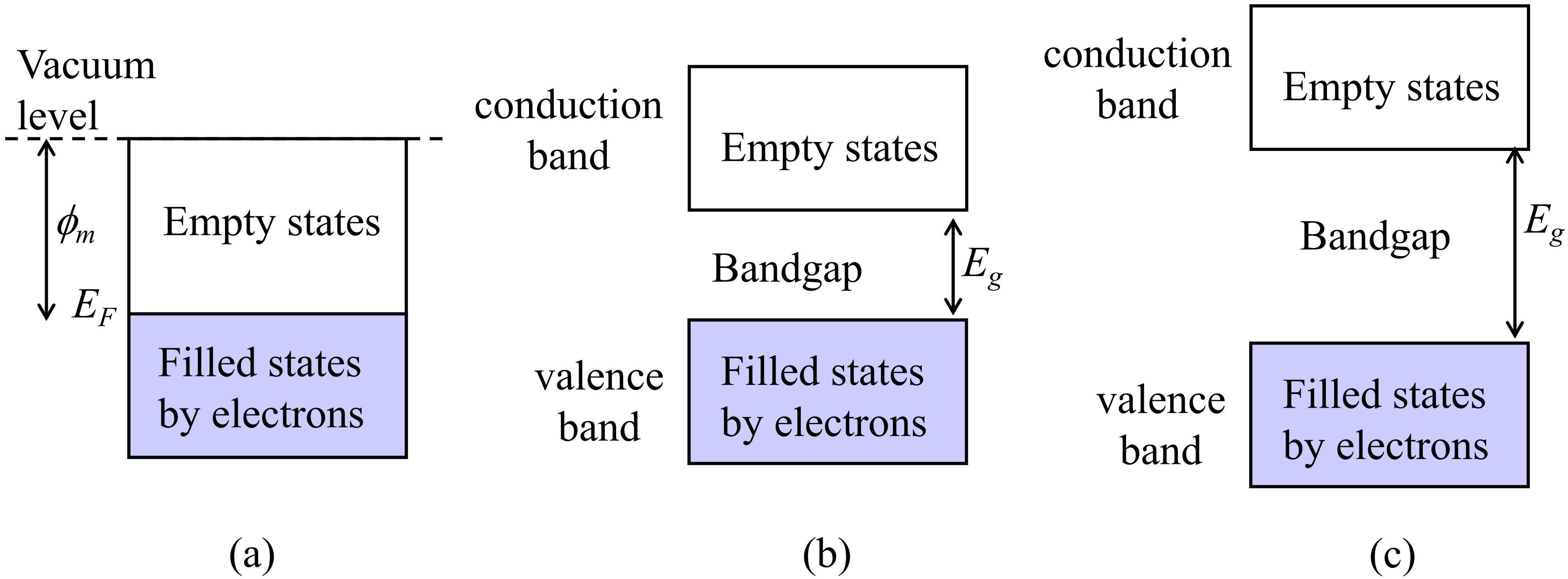


Fig. 1.2 Energy band structure of (a) metal, (b) semiconductor and (c) insulator

- In **metals**, the energy band is partially filled with electrons:
  - The energy of the highest occupied state at 0 K is referred to as the Fermi energy E_F .
  - Very little energy is required to promote electrons to the adjacent empty states.
  - Therefore metals are very good electrical conductors.
  - The minimum energy required for an electron to escape from a metal is called work function ϕ_m (energy from the Fermi level E_F to the vacuum level)

- For **semiconductors** & **insulators**, there are two bands separated by an energy gap or a bandgap E_g.
  - *No quantum states* in the energy gap ⇒ no electron is allowed there!

- For **insulators**, E_g is typically > 3eV.

$$\boxed{1 \text{ eV} = 1.60 \times 10^{-19} \text{ J} = 3.83 \times 10^{-20} \text{ calories}}$$

100 g of French fries → 300 Calories

- For **semiconductors**, E_g is typically tenths of fractions to 2 ~ 3eV.
  - At 0 K, all states in the lower band (*valence band*) are fully occupied by electrons & the upper band (*conduction band*) is empty. Hence, no electrical conduction.
  - For electrical conduction, electrons from the valence band have to be promoted to the empty conduction band.
  - Owing to their relatively small E_g, thermal energy at room temperature may excite some electrons from the valence band to the conduction band.

1.3 Main characteristics of a semiconductor

- Conductivity is neither very large nor very small
  - smaller than conductivity of good metals such as copper,
  - but much greater than insulators like glass.
- The conductivity can be varied over orders of magnitude by changes in temperature, optical excitation, electric field, and impurity content.

“Actors” in the conductivity process are:

- Electrons
  - An electron is a particle carrying an elementary charge of negative 1.6×10^{-19} Coulomb
- Holes
  - A hole is a “particle” in semiconductors that are able to produce current. A hole carries an elementary charge of positive 1.6×10^{-19} Coulomb
  - A hole is merely absence of an electron where it should be

Two general classifications of semiconductors

- Elemental semiconductors
  - Found in group IV of periodic table (see Table 1.1)
  - For examples, Silicon (most commonly used for ICs) and Germanium (used to make the first transistors and semiconductor diodes)
- Compound semiconductors
  - Special combinations of group III and group V elements
  - Two element, or binary, compounds. For example, gallium arsenide (GaAs) and indium phosphide (InP)
  - Three element, or ternary, compounds. For example aluminium gallium arsenide (AlGaAs)

Some questions to think about…

(1) Would it be possible to mix Si and Ge to form another type of semiconductor?

(2) Name one application for Si, Ge and GaAs.

Key takeaways (Lecture #2)

- Electronics configuration:
  - Each quantum state is unique, the higher the quantum state, the higher the energy of the electron
  - Incomplete subshell makes an atom chemically unstable
- Silicon:
  - Incomplete 3*p* subshell, need 4 more valence electrons
  - Form covalent bond (i.e. sharing of electron pairs) with 4 other Si atoms
  - Discrete quantum state $\rightarrow$ energy band
- Conduction in Silicon:
  - Valence band and conduction band are separated by a bandgap
  - Need empty state and electron/hole in these bands for conduction