Chapter 2-1. Semiconductor models

The subatomic particles responsible for charge transport in metallic wires – electrons

The subatomic particles responsible for charge transport in semiconductors – electrons & holes

In this chapter, we will study these topics:

The quantization concept
Semiconductor models
Carrier properties
State and carrier distributions
Equilibrium carrier concentrations

Quantization concept

In 1901, Max Planck showed that the energy distribution of the black body radiation can only be explained by assuming that this radiation (i.e. electromagnetic waves) is emitted and absorbed as discrete energy quanta - **photons**.

The energy of each photon is related to the wavelength of the radiation:

$$E = h\,\nu = h\,c / \lambda$$

where

h = Planck's constant ($h = 6.63 \times 10^{-34}$ Js)

ν = frequency (Hz = s^{-1})

c = speed of light (3×10^{8} m/s)

λ = wavelength (m)

Example

Our eye is very sensitive to green light. The corresponding wavelength is 0.555 μm or 5550 Å or 555 nm. What is the energy of each photon?

$$E = h\nu = \frac{6.62 \times 10^{-34}\ \text{Js} \times 3 \times 10^{8}\ \text{m/s}}{0.555 \times 10^{-6}\ \text{m}} = 3.57 \times 10^{-19}\ \text{J}$$

These energies are very small and hence are usually measured using a new energy unit called **electron Volts**

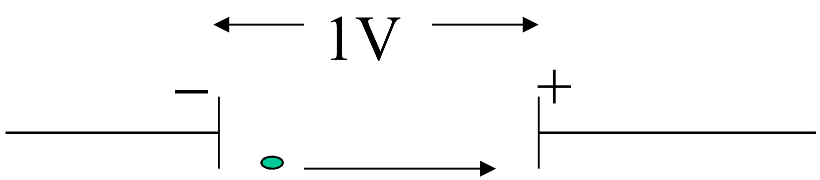
$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{CV} = 1.6 \times 10^{-19}\ \text{J}$

$$E_{\text{GREEN LIGHT}} = 2.23\text{eV}$$

A new unit of energy

Since the energies related to atoms and photons are very small, ($E_{\text{GREEN LIGHT}} = 3.57 \times 10^{-19}$ J), we have defined a new unit of energy called "electron Volt" or "eV"

One eV is the energy acquired by an electron when accelerated by a 1.0 V potential difference.



$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Energy acquired by the electron is qV. Since q is 1.6×10^{-19} C, the energy is 1.6×10^{-19} J. Define this as 1 eV. Therefore, $E_{\text{GREEN LIGHT}} = 2.23\text{eV}$

$$\boxed{1 \text{ eV} = 1 \times 1.6\times10^{-19} \text{ CV} = 1.6\times10^{-19} \text{ J}}$$

Quantization concept (continued):

Niels Bohr in 1913 hypothesized that electrons in hydrogen was restricted to certain discrete levels. This comes about because the electron waves can have only certain wavelengths, i. e. $n\lambda = 2\pi r$, where r is the orbit radius. ➔ **Quantization**

Based on this, one can show that:

$$E_{\mathrm{H}} = -\frac{m_0 q^4}{2(4\pi\varepsilon_0 \hbar n)^2} = -\frac{m_0 q^4}{8 \varepsilon_0^2 n^2 h^2} \qquad \text{for} \qquad n = 1, 2, 3\ldots$$

$$\text{where} \quad \hbar = \frac{h}{2\pi} \qquad \text{and} \qquad h = \text{Planck's constant}$$

Bohr's hydrogen atom model

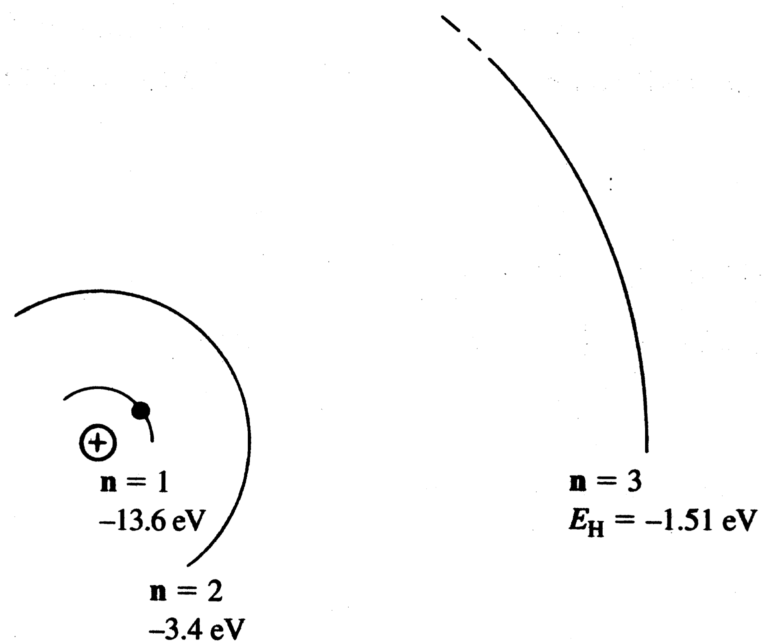


Figure 2.1

A numerical example:

$$E_n = -\frac{m_0 q^4}{8\,\varepsilon_0^2\, n^2\, h^2} = -\frac{9.11\times10^{-31}\ \text{kg}\times\left(1.6\times10^{-19}\ \text{C}\right)^4}{8\times\left(8.85\times10^{-12}\ \text{F/m}\right)^2\times1\times\left(6.62\times10^{-34}\ \text{Js}\right)^2}$$

$$= -21.7\times10^{-19}\ \text{J} = -13.5\ \text{eV} \ \text{ for the } n=1 \text{ orbit}$$

For the $n = 2$ orbit, $E_2 = -3.4$ eV and so on. The number ***n*** is called the principal quantum number, which determines the orbit of the electron.

Since Hydrogen atom is 3-D type, we have other quantum numbers like, **l** and **m** within each orbit. So, in atoms, each orbit is called a “shell” .

See *Appendix A* in text for the arrangement of electrons in each shell and also for various elements in the periodic table.

Atomic configuration of Si

So, an important idea we got from Bohr model is that the energy of electrons in atomic systems is restricted to a limited set of values. The energy level scheme in multi-electron atom like Si is more complex, but intuitively similar.

Ten of the 14 Si-atom electrons occupy very deep lying energy levels and are tightly bound to the nucleus

The remaining 4 electrons, called valence electrons are not very strongly bound and occupy 4 of the 8 allowed slots.

Configuration for Ge is identical to that of Si, except that the core has 28 electrons.

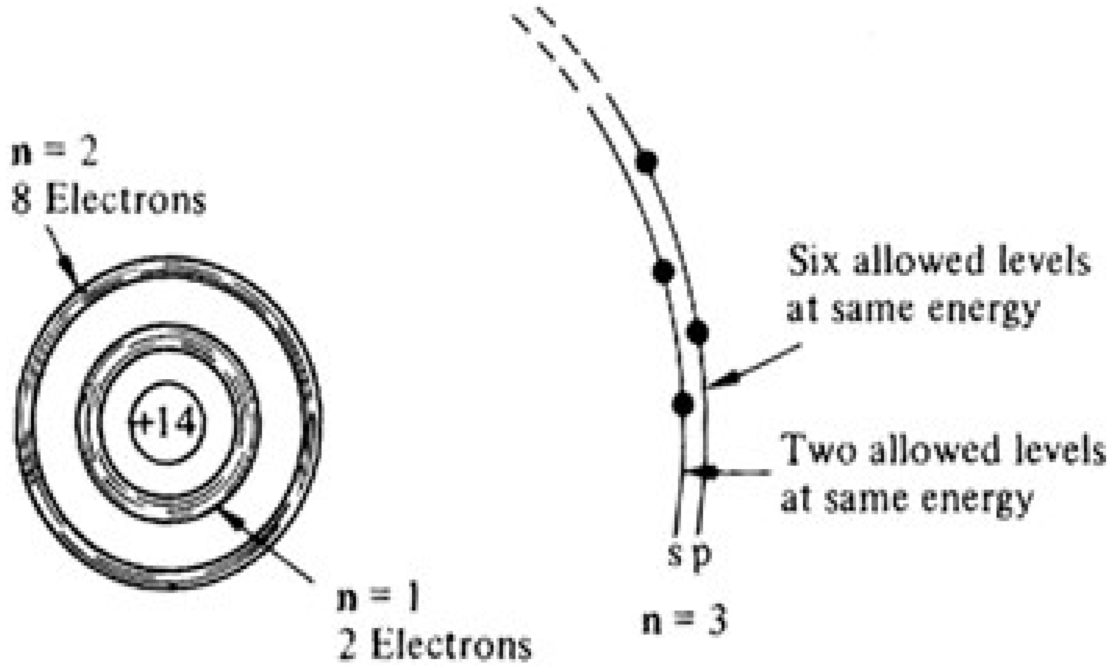


Figure 2.2 Schematic representation of an isolated Si atom.

Bond model

Consider a semiconductor Ge, Si, or C

Ge, Si, and C have four nearest neighbors, each has 4 electrons in outer shell

Each atom shares its electrons with its nearest neighbor. This is called a covalent bonding

No electrons are available for conduction in this covalent structure, so the material is and should be an insulator at 0 K

2-dimensional (2D) semiconductor bonding model

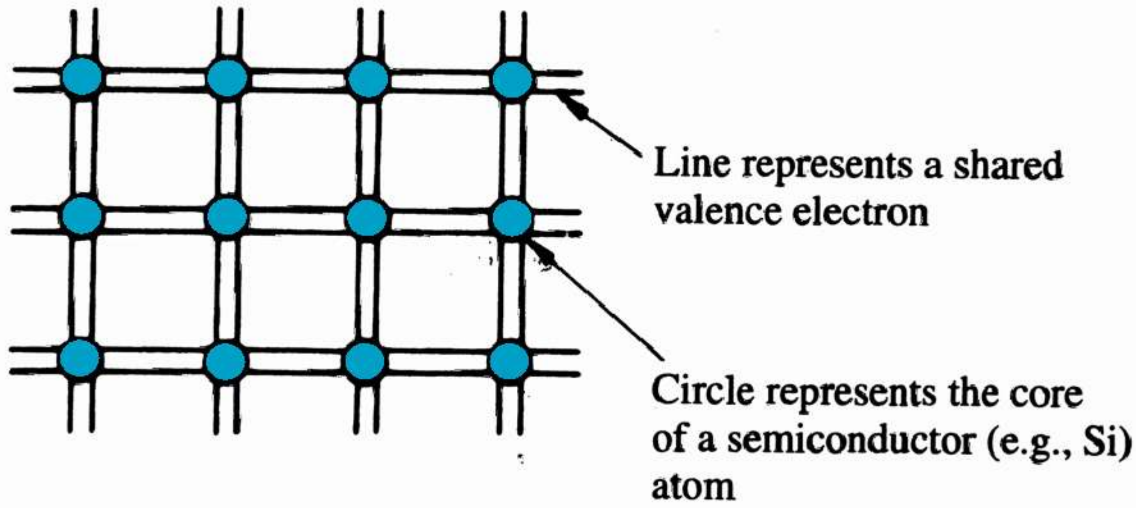
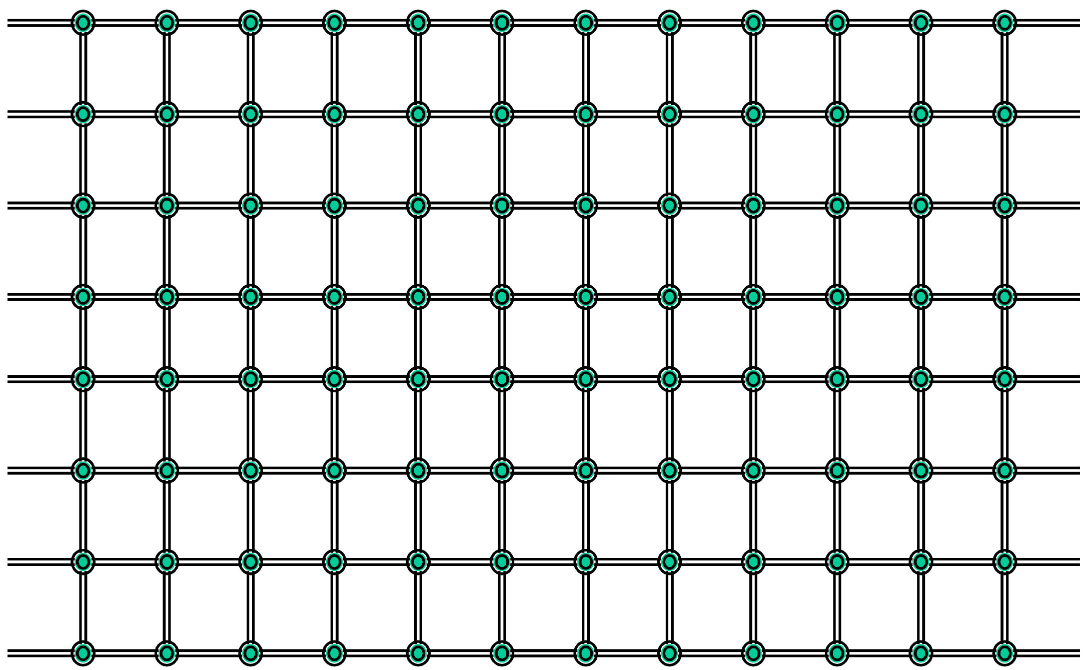


Figure 2.3

No electrons are available for conduction. Therefore, Si is an insulator at $T = 0$ K.

Simplified 2D representation of Si lattice



- How many atom-neighbors has each Si atom in a Si lattice?
- How many electrons are in the outer shell of an isolated Si atom?
- How many electrons are in the outer shell of a Si atom with 4 neighbors?

(a) Point defect (b) Electron generation

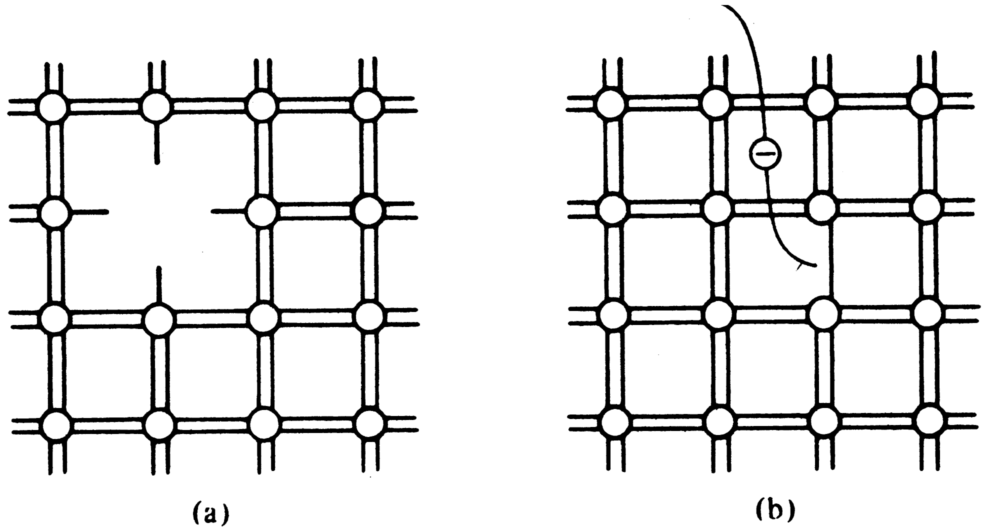


Figure 2.4

At higher temperatures (e.g. 300 K), some bonds get broken, releasing electrons for conduction. A **broken bond** is a **deficient electron** of a **hole**. At the same time, the broken bond can move about the crystal by accepting electrons from other bonds thereby creating a hole.

Energy band model

An isolated atom has its own electronic structure with $n = 1, 2, 3 \ldots$ shells.

When atoms come together, their shells overlap.

Consider Silicon: Si has 4 electrons in its outermost shell, but there are 8 possible states. When atoms come together to form a crystal, these shells overlap and form bands.

We do not consider the inner shell electrons since they are too tightly coupled to the inner core atom, and do not participate in anything.

Development of the energy-band model

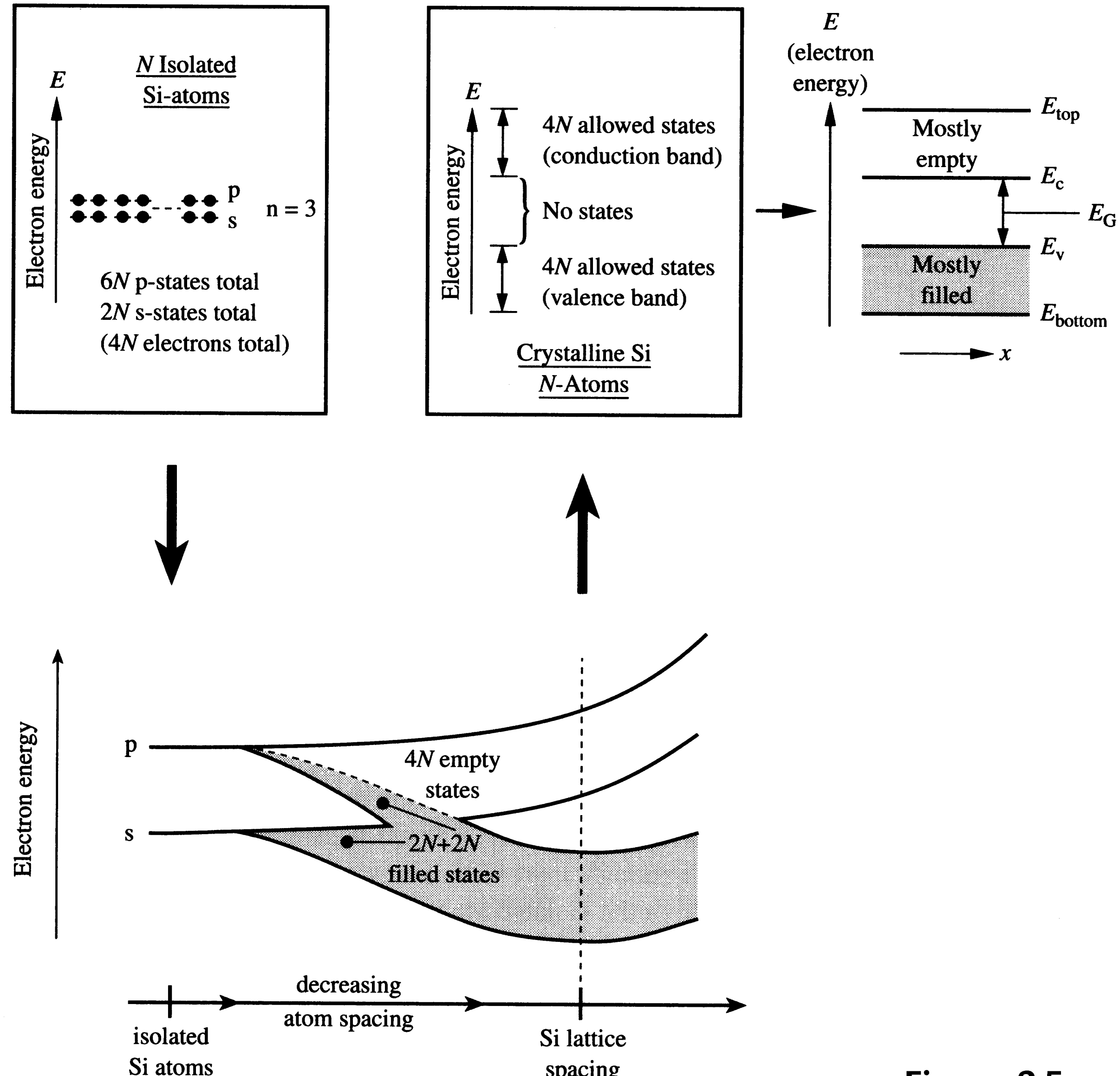


Figure 2.5

Energy band model

At $T = 0K$

No conduction can take place since there are no carriers in the conduction band.

Valence band does not contribute to currents since it is full.

Actually, valence electrons do move about the crystal.

- No empty energy state available

- For every electron going in one direction there is another one going in the opposite direction. Therefore: Net current flow in filled band = 0

Both bond model and band model shows us that semiconductors behave like **insulators** at **0K**.

Visualization of carriers using energy bands

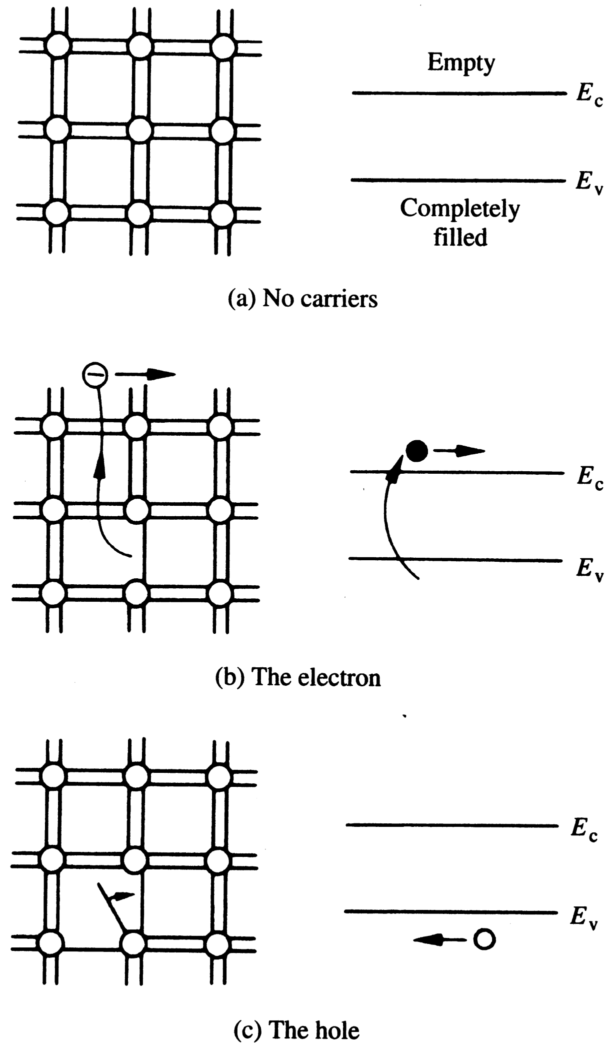


Figure 2.7

Insulators, semiconductors, and metals

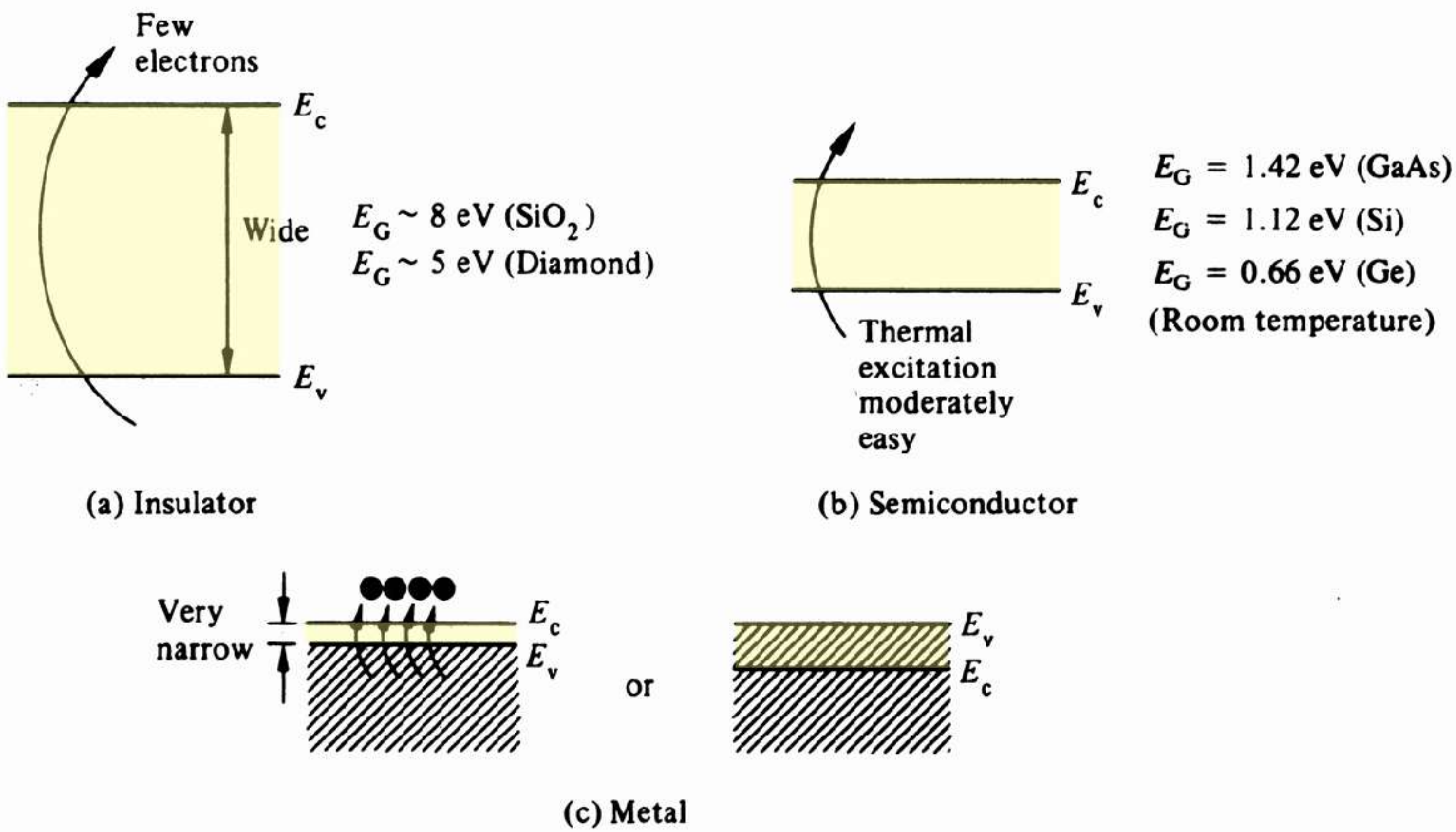


Figure 2.8