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Chinmoy Saha , Arindam Halder , Debarati Ganguly
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Chapter 1

Introduction to Electronics: Basic Ideas

1.1 INTRODUCTION

Electronics, evolved from the word 'electron' (a sub-atomic particle carrying negative charge), is the branch of science and engineering dealing with the study, design and use of devices that depend on the conduction of electricity through vacuum, gas or semiconductor, contributed by the transport phenomenon of the electrons. Earlier, electronics or electronics engineering used to be considered as an integral part of electrical engineering. However, due to the tremendous growth of electronics and its unprecedented applications in various fields over the last few decades, it has evolved as a separate branch of engineering. In addition, due to its widespread application in almost all possible branches of engineering and science, acquiring basic understanding of electronics and fundamentals of electronic devices has become a common requirement for students of all engineering disciplines.

Before we discuss the details of the preliminary concepts required to understand the basic ideas of electronics, let us have a look at the chronological growth of modern electronics:

1850: Geissler, a German scientist, demonstrated the flow of electric current through a vacuum glass tube.
1878: Sir William Crookes, a British scientist, showed how current in vacuum tubes appears to consist of particles.
1890: Perrin, a French physicist, demonstrated that current in vacuum tube is due to the movement of negatively charged particles.
1897: Sir J. J. Thomson, a British physicist, measured some of the properties of the "negatively charged particle" (cathode ray) contributing to current in vacuum tube (named as cathode ray tube). He concluded that these particles are much smaller than atoms possessing high specific charge (charge to mass ratio). Thus, he is credited with the discovery of the first sub-atomic particle (later named as electron).

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1904: John Ambrose Fleming, a British physicist, invented vacuum tube that allows current only in one direction. This was named as Fleming valve- the primitive version of a diode- and was also known as vacuum tube or vacuum diode.

1907: Lee de Forest, an American scientist, invented a tube which could amplify weak electrical AC signal. This tube, a primitive version of the transistor, was named as vacuum triode.

1909: Robert Millikan, an American physicist, measured the charge of an electron.

1947: Walter Brattain, John Bardeen and William Shockley of Bell Laboratory, USA invented the transistor. This is considered as the beginning of a new era of electronics in the form of solid-state electronics.

1951: Commercial realization of transistors by companies like RCA, Raytheon, General Electric, Westinghouse and Western Electric.

1958: Conceptual realization of a full circuit on silicon and germanium, called monolithic circuit.

1961: Commercial realization of Integrated Circuits (IC) by companies like Texas Instrument and Fairchild. Jack Kilby and Robert Noyce were the first to invent IC.

Since the invention of modern transistor in 1947, electronics industry started experiencing unprecedented growth due to its various applications, especially for civilian, commercial and defence use. The invention of the IC and the quest for realizing miniaturized high-speed electronic circuits for various applications dramatically changed the entire electronics industry in the next few decades. The demand for compact electronic gadgets caused rapid change in the technology and various levels of integration, SSI (Small Scale Integration), MSI (Medium Scale Integration), LSI (Large Scale Integration) and VLSI (Very Large Scale Integration), were realized. This growth in electronics industry made the vacuumtube-based electronic devices almost obsolete since the 1960s. Similarly, growth in ICs has almost stopped the use of individual transistors. Thus, modern electronic circuits and gadgets are completely based on solid-state (semiconductor-based) electronic circuits, realized on a single semiconductor wafer, called Integrated Circuits. Modern ICs are realized with large number of extremely compact transistors (~mm dimension) embedded in a single platform and they are capable of performing arithmetic, logical and memory operations as well. The basic example of this type of IC is the microprocessor.

Today, the impact of modern electronics is so extensive that it plays a major role in every activity of our life. It controls our daily life at our home and office, as well as our means of communication. The applications of modern electronics are as follows:

• Entertainment application:	TV, radio, music player, etc.
• Communication:	Radio, TV, telephone, mobile, etc.
• Instrumentation:	All measuring instruments are based on electronics.
• Control:	Various civilian and defence applications
• Defence application:	Radar, aeroplanes, ships, anti-aircraft guns, missile, underwater robots
• Remote sensing:	Weather forecast, climatology

- Medical applications: X-ray, ECG, USG, MRI, laser-based surgery and treatment, etc.
- Computer-aided design: Various research tools and software are useful

Figure 1.1 illustrates the various areas of modern electronics engineering.

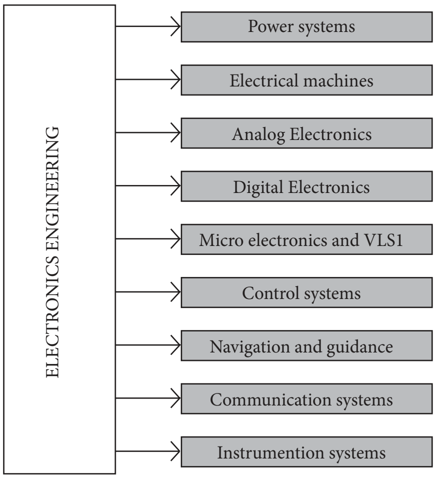

Figure 1.1 Various components of electronics engineering

1.2 ATOMIC STRUCTURE: BOHR'S MODEL

An atom is the most fundamental unit of an element that retains the characteristics of that element. Each of the available 109 elements has a unique atomic structure. Since the fundamental atomic structure is related to various properties and characteristics of the element (like thermal, electrical, mechanical, chemical, etc.), it is considered as the most basic building block even in modern physical science. You have studied the details of atomic structure in your school (X & XII level). Here, we will quickly revisit that in a brief manner.

According to the classical Bohr's model, atoms have a planetary like structure that consists of a central region called 'nucleus' and orbital electrons surrounding it. The nucleus is made up of positively charged particles called protons and uncharged particles called neutrons. Each of the orbiting electrons carry negative charge, same in magnitude as that of protons. Thus, the core an atom, nucleus, is positively charged and surrounded by negatively charged electrons revolving in fixed circular/elliptical orbits. The orbits in which electrons can exist are called stationary orbits and is described by Bohr's condition ($mvr = nh/2\pi$). Each of these orbits corresponds to a different energy level, which takes a crucial role in absorption/emission spectra of the atoms.

The cumulative effect of all revolving electrons around the nucleus is described by a negatively charged 'electron cloud'. The revolving electrons maintain their equilibrium by the electrostatic force between electron cloud and nucleus balanced by the centripetal force. In a normal atom, the number of electrons is equal to the number of protons, which ensures that atoms are electrically neutral.

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1.2.1 Electron Orbits

We know from our previous knowledge of atomic theory that electrons revolve around the nucleus in certain fixed allowable orbits. Each of these allowed orbits are known as energy levels or shells. These energy levels are indicated by an integer n called principal quantum number. Based on the value of n ($n = 1, 2, 3, ...$), the orbits are represented as K, L, M, N, etc. corresponding to $n = 1, 2, 3, 4$, etc. as shown in Figure 1.2. Since the maximum number of electrons in any shell is governed by the relation $2n^2$, these shells can have a maximum of electrons as indicated in Table 1.1.

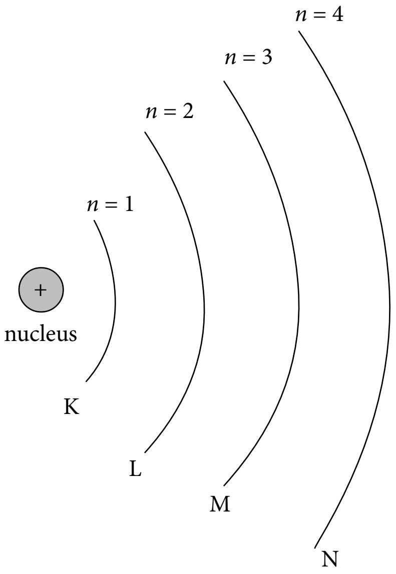

Figure 1.2 Different electron orbits of an atom

TABLE 1.1

$n = 1$, K shell	$n = 2$ L shell	$n = 3$ M shell	$n = 4$ N shell
$2.1^2 = 2$	$2.2^2 = 8$	$2.3^2 = 18$	$2.4^2 = 32$

In addition, the distribution of electrons in an atom is also subject to the following conditions:

i) The outermost shell of an atom cannot accommodate more than 8 electrons, even if it has a higher capacity to do so.
ii) The shell of an atom prior to the outermost shell cannot accommodate more than 8 electrons.

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1.2.2. Distribution of Electrons in Atoms

Since most of the modern electronic devices are fabricated by semiconductor materials, we will discuss the electronic configuration for some of the most widely used semiconductors like silicon (Si), germanium (Ge), etc. Table 1.2 shows a portion of the periodic table in which more common semiconductors are found. Let us choose boron (B), silicon (Si), germanium (Ge) and phosphorus (P).

Boron

Atomic number of boron is 5. It means that out of 5 available electrons, 2-electrons occupy K-shell ($n = 1$) and 3-remaning electrons occupy L-shell ($n = 2$). Using the concept of sub-shells (s, p, d, f) the electronic configuration of Boron can be written as $B(5) \longrightarrow 1s^2\ 2s^2\ 2p^1$.

Thus, it has 3 valence electrons.

TABLE 1.2 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 Ir Iridium		**51** Sb Antimony

Silicon

Atomic number of Si is 14. So it has 14 protons and 14 electrons. These 14 available electrons are distributed in 2 + 8 + 4 fashion in K-shell ($n = 1$), L- shell ($n = 2$) and M-Shell ($n = 3$) respectively, as indicated in Figure 1.3. Thus, a silicon atom has 4 valance electrons.

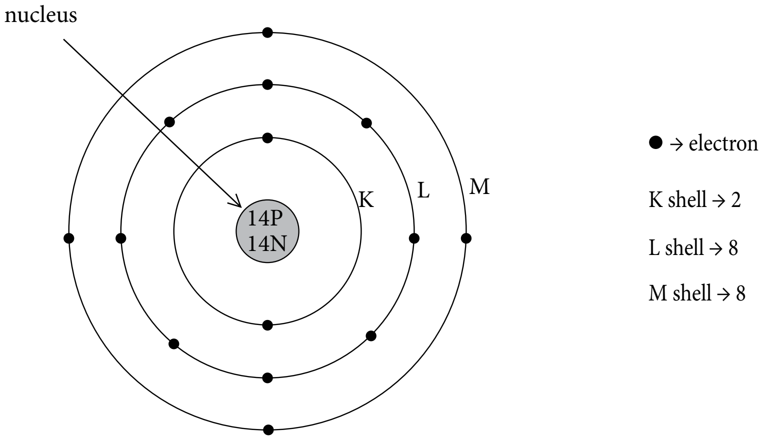

Figure 1.3 Silicon atom

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Electronic configuration of silicon is Si (14) → $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$

In a similar way, we can find the electronic configuration of any other atom. Two cases of interest for material of electronic devices are atoms on the immediate left and right of Si, i.e., aluminum (Al) and phosphorus (P). Al, with an atomic number of 13, has the electronic configuration $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$, i.e., it has 3 valence electrons. On the other hand, phosphorus (15) has an electronic configuration of $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$. Thus, it has 5 valence electrons. Element just below Si is Ge, having an atomic number of 32. It is another important material for electronic devices. It has an electronic configuration of $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$. Like Si, Ge atom has 4 valence electrons.

1.3 BONDING IN SOLID: COVALENT BONDS

To have a clear understanding of how certain materials (Si, Ge, etc.) are preferred as automatic choice for electronic devices, we require the basic understanding of how individual atoms are bound together to form a crystalline structure. Atoms within a crystalline solid are held together by various kinds of mutual interaction/inter-atomic forces called inter-atomic bonds. Depending on the mechanism of the formation of the bonds, there can be various types like ionic bond, covalent bond, metallic bond, etc. Due to their wide application in solid-state electronics, here we will discuss preliminary concepts of covalent bonding with a special emphasis on the popular electronic materials.

Covalent bond

This is formed by the sharing of electrons between atoms. The sharing of electrons occurs in a way so that each atom of the resulting molecule attains a stable electronic configuration (similar to that of an inert/noble gas). Covalent bonds are very common in non-metals having 5, 6 or 7electrons in the outermost energy level of their atoms. Also, covalent bonds are easily formed in tetravalent elements like Si and Ge, which have four electrons in their outermost energy level.

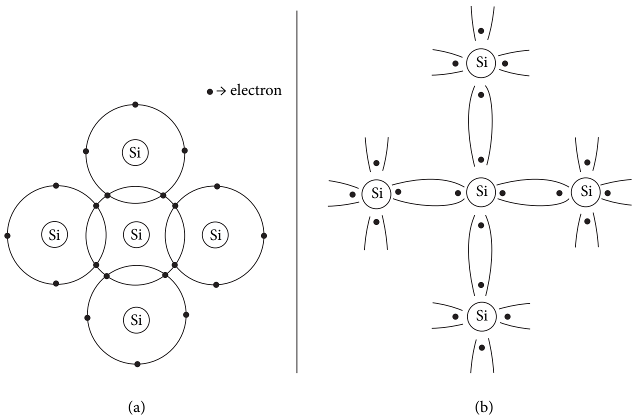

Figure 1.4 Formation of covalent bond in Si crystal

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Figure 1.4(a) shows the formation of covalent bonds in Si atom. As it has four electrons in its outermost shell, it requires four more electrons to fulfill octet and thereby become stable. As shown in Figure 1.4, a Si atom with four valence electrons shares an electron with each of its neighbouring Si atoms. This effectively provides eight valence electrons for each atom and produces stability. Figure 1.4(b) shows the bonding diagram in Si. Covalent bonding for Ge is exactly similar to this, as it also has four valence electrons.

Covalent bond can also form between dissimilar atoms. One case of interest for us is bonding between gallium (Ga) and arsenic (As) atoms, forming a compounding semiconductor, gallium arsenide (GaAs).

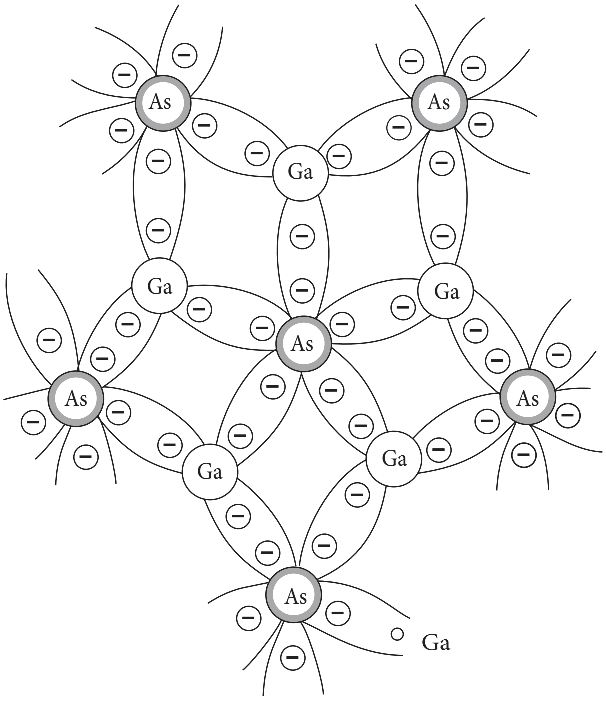

Figure 1.5 Covalent bonding in GaAs crystal

Figure 1.5 shows the covalent bonding where each Ga or As atom is surrounded by the atoms of the complementary type. Here, sharing of electrons is similar to Si atoms, but 5 electrons are provided by As atoms and 3 by Ga atom.

Although all the shared electrons forming the covalent bond between atoms are still associated with their parent atoms, it is possible for them to become 'free' when energized properly. The valence electrons, if supplied with adequate amount of thermal or optical energy, can break the covalent bond and thereby become almost 'free'. Natural optical/thermal energy in most cases is good enough to create such 'free' electrons. Motion of such electrons in a crystal can be controlled by external electric field, which is the basis of the working principle of all electronic devices. Concentration of such free carriers in a crystal

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takes a crucial role in determining various electrical/electronic characteristics. Table 1.3 compares the number of such free carriers (n_i) per cubic centimeter for Ge, Si & GaAs. This free carrier concentration is also known as intrinsic carrier concentration.

TABLE 1.3 Carrier concentration in common semiconductor

Material	Intrinsic carrier concentration (n_i)
GaAs	1.7×10^{6}
Si	1.5×10^{10}
Ge	2.5×10^{13}

1.4 ENERGY LEVELS

According to Bohr's model of atomic theory, electron revolves around the nucleus in certain discrete circular orbits. Each of these allowable orbits of the electrons are called fixed orbits and are governed by the condition that angular momentum of the electrons must be an integral multiple of $h/(2\pi)$, where h is Planck's constant and $n = 1, 2, 3, \ldots$ corresponding to different orbits.

It can be shown that total energy of an electron revolving in the n-th orbit of an atom having atomic number Z is given by

$$E_n = -13.6 \times \frac{Z^2}{n^2} \qquad \text{(1.1) (in electron volt)}$$

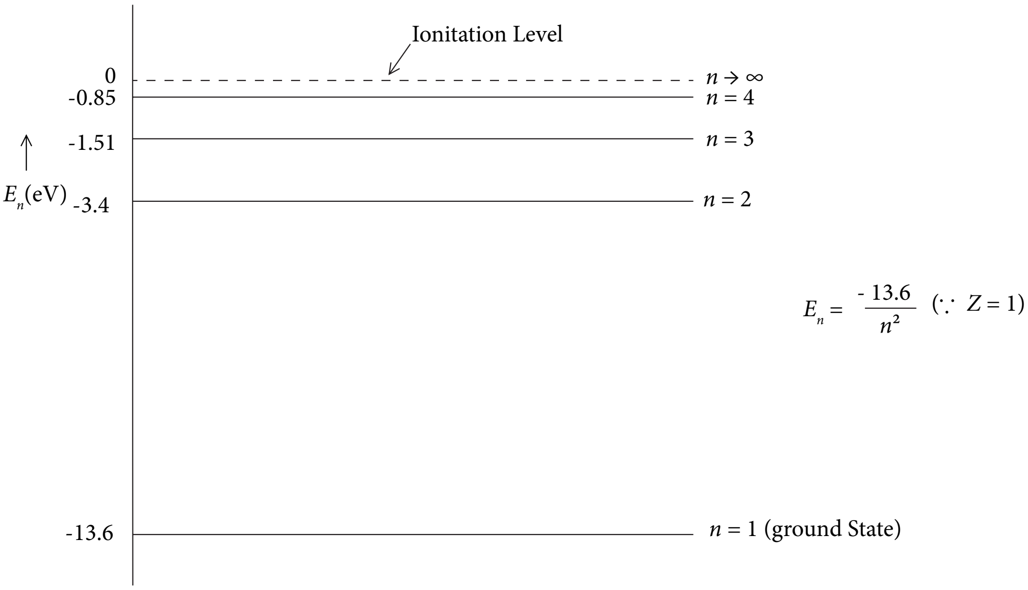

Figure 1.6 Energy level in Hydrogen atom

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From equation (1) it is very clear that each discrete value of n ($n = 1, 2, 3, \ldots$) corresponds to a specific energy value. This means that electrons in an atom can have only certain specific values of energy. These allowable energy levels for a Hydrogen atom ($Z = 1$) is indicated in Figure 1.6. Here $n = 1$, corresponding to $E_1 = -13.6$ eV, indicates the ground state energy level and $n = 2$, corresponding to $E_2 = -\frac{E_1}{4} = -3.4$ eV, indicates the next allowed energy level. Thus, with increasing value of n, energy value of the electron increases and approaches zero ($E_n = 0$) when $n \to \infty$. This zero energy level of electron (for $n \to \infty$) is also known as ionization level, as when an electron reaches this energy level it becomes free and as a result the atom is ionized. An electron must be supplied energy externally to reach this level. On the other hand, when an electron jumps from higher energy state to a lower energy state, it emits a photon of frequency γ given by

$$\gamma = \frac{E_h - E_l}{h} \tag{1.2}$$

Where E_h and E_l indicate higher and lower energy states of the electron.

If an electron jumps from $n = 3$ level to $n = 2$ level, emitted photon energy is

$$E_{photon} = -1.51 - (-3.4) = 1.89 \text{ eV}$$

On the other hand, if the electron jumps from $n = 3$ level to $n = 1$ level, the emitted photon energy is

$$E_{photon} = -1.51 - (-13.6) = 12.09 \text{ eV}$$

Such emitted photons give rise to the emission spectra of any atom.

In a normal atom, electrons occupy the lowest energy state, called ground state. It can reach the higher energy state, called excited state, by absorbing photons of suitable energy.

1.5 ENERGY BAND

We are already familiar with the concept of discrete energy levels for the electrons in an atom. This concept of discrete energy levels is strictly applicable only for isolated atoms. When a large number of atoms come in close proximity, the concept of discrete energy levels is changed quite a bit. When a large number of atoms are brought very close to each other to form a crystal, each atom exerts an electric force on its neighbour. Due to these strong mutual inter-atomic interactions, the allowed energy levels of the individual atoms 'split' into very closely spaced energy levels. This splitting of energy levels can also be understood using Pauli's exclusion principle. According to this principle, in a particular sub-shell, maximum two number of electrons can be accommodated. Thus, if two atoms come into close proximity, and their energy levels are unaffected, there might be four number of electrons in 1s–sub-level, four number of electrons in 2s–sub–level, etc., which is against Pauli's exclusion principle. Therefore, each energy level of the isolated atoms,

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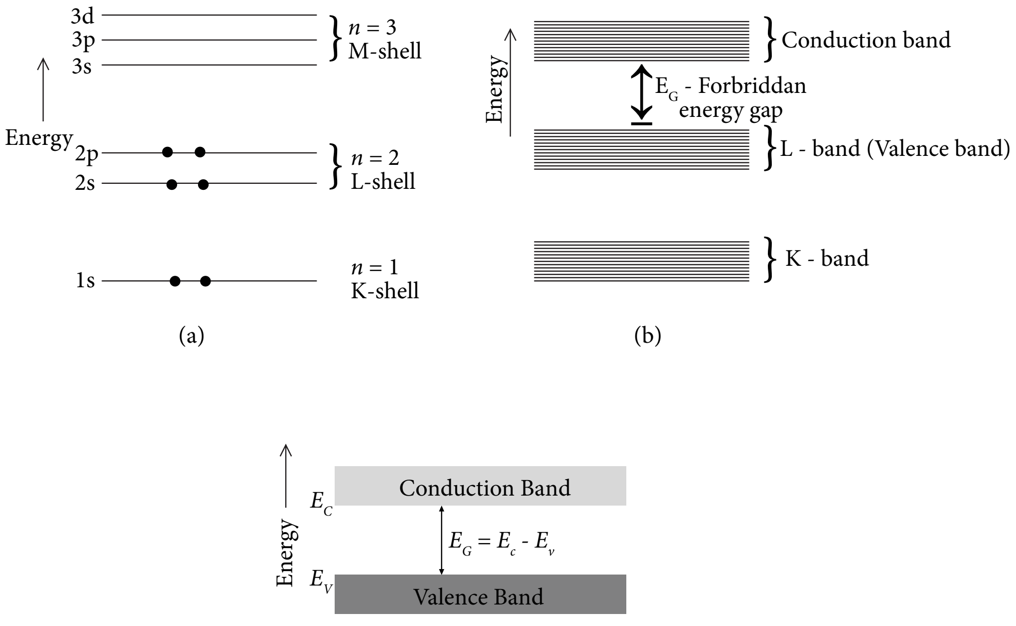
splits into as many energy levels as there are atoms in the crystal. This splitting of individual energy levels due to interaction of large number of atoms while forming a solid keeps Pauli's exclusion principle valid (if N number of atoms interact, there will N number of 1s level, 2s level, 2p level...). The separation between the split energy levels is very small. However, due to large number of atoms ($\approx 10^{23}$ atom/cm^3), each individual energy level of isolated atoms are split into large energy levels very close to each other. This large number of discrete, but very closely spaced, energy levels is called energy bonds.

To better understand the qualitative concept of energy band in a crystal, let us consider an example. First, we consider an isolated carbon ($Z = 6$) atom and then a large number of atoms to form a crystal of carbon atoms.



(a) (b)

(c)

Figure 1.7 Formation of energy bond in a carbon crystal
(a) Energy level diagram of isolated carbon atom, (b) split energy levels in cluster of carbon atoms in close proximity while forming the crystal (c) simplified view of (b) showing the top two energy bands only.

Figure 1.7(a) shows the energy levels of an isolated carbon atom having atomic configuration $1s^2\,2s^2\,2p^2$. Thus, it has two electrons in K-shell ($n = 1$) and four electrons in L-shell, while M-shell ($n = 3$) is completely empty. When large number of carbons atoms interact with each other while forming the crystal, each of the energy levels are split as shown in Figure 1.7(b). It is evident from Figure 1.7(b) that large number of K-shells of various atoms with tiny separation form K-band. Similarly, energy levels corresponding to the $n = 2$ shell form L-band. Since $n = 2$ shell corresponds to the valence electrons (outermost shell electrons) in carbon atom, L- band is contributed by energy splitting of all

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