Electronics Engineering

Electronic Devices and Circuits

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Introduction

Since this book is primarily an introduction to solid state devices, it would be preferable not to delay this discussion with subjects such as atomic theory, quantum mechanics, and electron models. However, the behaviour of solid state devices is directly related to these subjects. For example, it would be difficult to understand how an electron is transported through a semiconductor device without some knowledge of the electron and its interaction with the crystal lattice. Therefore, in this chapter we shall investigate some of the important properties of electrons, with special emphasis on two points: (1) the electronics structure of atoms, and (2) the interaction of atoms and electrons with excitation, such as the absorption and emission of light.

We begin with a review of the basic atomic properties of matter leading to discrete electronic energy levels in atom. We find that atomic energy levels are spread into energy bands in a crystal. This band structure allows us to distinguish between an insulator, a semiconductor, and a metal.

1.1 The Nature of The Atom

In order to explain many phenomena associated with conduction in gases, metals and semiconductors and the emission of electrons from the surface of a metal, it is necessary to assume that the atom has loosely bound electrons which can be torn away from it.

Rutherford found that the atom consists of a nucleus of positive charge that contains nearly all the mass of the atom and hence it will remain substantially immobile. Surrounding this central positive core are negatively charged electrons. As a specific illustration of this atomic model, consider the hydrogen atom. This atom consists of a positively charged nucleus (a proton) and a single electron. The force of attraction between the electron and the proton follows Coulomb's law. It can be shown from classical mechanics that the resultant closed path will be a circle or an ellipse under the action of such a force. This motion is exactly analogous to that of the planets about the sun, because in both cases the force varies inversely as the square of the distance between the particles.

Assume, therefore, that the orbit of the electron in this planetary model of the atom is a circle, the nucleus being supposed fixed in space. It is a simple matter to calculate its radius in terms of the total energy W of the electron. The force of attraction between the nucleus and the electron is $e^2/4\pi \in_0 r^2$, where the electronic charge e is in Coulombs, the separation r between the two particles is in meters, the force is in Newtons, and $\in_0$ is the

permittivity of free space. By Newtons's second law of motion, this must be set equal to the product of the electronic mass m in kilograms and the acceleration $\dfrac{v^2}{r}$ toward the nucleus, where v is the speed of the electron in its circular path, in meters per second.

Then

$$\frac{e^2}{4\pi \in_0 r^2} = \frac{mv^2}{r} \qquad \qquad ...(1.1)$$

Furthermore, the potential energy of the electron at a distance r from the nucleus is $-e^2/4\pi \in_0 r$, and its kinetic energy is $\dfrac{1}{2} mv^2$. Then, according to the conservation of energy,

$$W = \frac{1}{2} mv^2 - \frac{e^2}{4\pi \in_o r} \qquad \qquad ...(1.2)$$

where the energy is in Joules. Combining equation (1.2) with equation (1.1) we get

$$W = -\frac{e^2}{8\pi \in_0 r} \qquad \qquad ...(1.3)$$

which gives the desired relationship between the radius and the energy of the electron. This equation shows that the ***total energy of the electron is always negative***. The negative sign arises because the potential energy has been chosen to be zero when r is infinite. This expression also shows that the energy of the electron becomes smaller (i.e., more negative) as it approaches closer to the nucleus.

However, an accelerated charge must radiate energy, in accordance with the classical laws of electromagnetism. If the charge is performing oscillations of a frequency f, the radiated energy will also be of this frequency. Hence, classically, it must be concluded that the frequency of the emitted radiation equals the frequency with which the electron is rotating in its circular orbit.

But if the electron is radiating energy, its total energy must decrease by the amount of this emitted energy. As a result the radius r of the orbit must decrease, in accordance with Equation (1.3). Consequently, as the atom radiates energy, the electron must move in smaller and smaller orbits, eventually falling into the nucleus. Since the frequency of oscillation depends upon the size of the circular orbit, the energy radiated would be of a gradually changing frequency. Such a conclusion, however, is incompatible with the sharply defined frequencies of spectral lines.

1.1.1 The Bohr Atom

Above difficulty was resolved by Bohr. He postulated the following three fundamental laws:

(*i*) Not all energies as given by classical mechanics are possible, but the atom can possess only certain discrete energies. While in states corresponding to these discrete energies, the electron does not emit radiation, and the electron is said to be in stationary or non-radiating, state.

(*ii*) In a transition from one stationary state corresponding to a definite energy W_2 to another stationary state, with an associated energy W_1, radiation will be emitted. The frequency of this radiant energy is given by

$$f = \frac{W_2 - W_1}{h} \qquad \qquad ...(1.4)$$

where h is Planck's constant in Joule-seconds, the W's are expressed in Joules, and f is in cycles per second, or Hertz.

(*iii*) A stationary state is determined by the condition that the angular momentum of the electron in this state is quantized and must be an integral multiple of $h/2\pi$. Thus

$$mvr = \frac{nh}{2\pi} \qquad \ldots(1.5)$$

where n is an integer.

Combining Eq. (1.1) and (1.5), we obtain the radii of the stationary states, and from Eq. (1.3) the energy level in Joules of each state is found to be

$$W_n = -\frac{me^4}{8h^2\epsilon_0^2} \cdot \frac{1}{n^2} \qquad \ldots(1.6)$$

Example - 1.1 As the Fermi energy of silver is 8.8×10^{-19} Joule, the velocity of the fastest electron in silver at 0°K (Given: Rest mass of electron = 9.1×10^{-31} kg) is

(a) 3.33×10^5 m/s   (b) 1.39×10^6 m/s

(c) 4.40×10^7 m/s   (d) 3×10^8 m/s

Solution : (b)

$$\frac{1}{2}mv^2 = E \quad \text{or} \quad v^2 = \frac{2E}{m}$$

or

$$v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2 \times 8.8 \times 10^{-19}}{9.1 \times 10^{-31}}} = 1.39 \times 10^6 \text{ m/s}$$

1.2 Atomic Energy Levels

For each integral value of *n* in Eq. (1.6) a horizontal line is drawn. These lines are vertically in accordance with the numerical values calculated from Eq. (1.6). Such a convenient pictorial representation is called an *energy level diagram* and is indicated in Fig. (1.1) for hydrogen. The number to the left of each line gives the energy of this level in electron volts. The number immediately to the right of a line is the value of *n*. Theoretically, an infinite number of levels exist for each atom, but only the first five and the level for *n* = ∞ are indicated in Fig. (1.1).
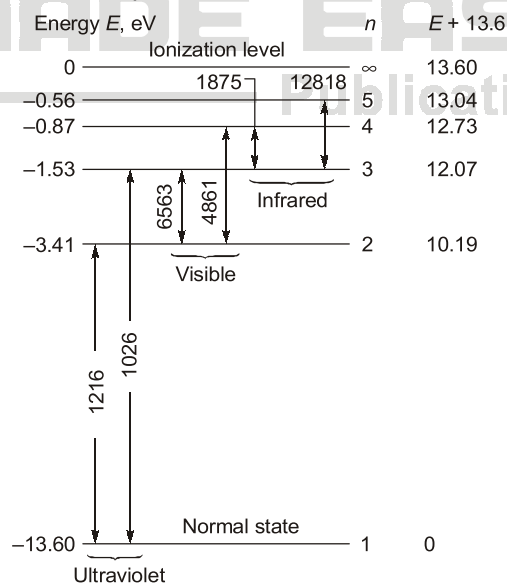
Figure-1.1 : *The lowest five energy levels and the ionization level of hydrogen. The spectrum lines are in angstrom units*

It is customary to express the energy value of the stationary states in electron volts E rather than in Joules W. Also, it is more common to specify the emitted radiation by its wavelength λ in angstroms rather than by its frequency f in Hertz. In these units, Equation (1.4) may be rewritten in the form

$$\lambda = \frac{12,400}{E_2 - E_1} \qquad \qquad ...(1.7)$$

NOTE

The eV unit of Energy:

The joule (J) is the unit of energy in the MKS system. However, in electronics engineering problems, the joule is too large a unit. So practical unit for the energy in electronics engineering is **electron volt (eV)** and is defined as the energy gained by the electron in moving through a potential difference of 1V i.e.

$$1\ eV = |q| \times \text{potential difference}$$
$$= 1.6 \times 10^{-19}\ (C) \times 1\ (\text{volt}) = 1.6 \times 10^{-19}\ (C \cdot \text{volt})$$

$$\boxed{1\ eV = 1.6 \times 10^{-19}\ (\text{Joule})}$$

Example - 1.2   The longest wavelength that can be absorbed by silicon, which has the bandgap of 1.12 eV, is 1.1 μm. If the longest wavelength that can be absorbed by another material is 0.87 mm, then the bandgap of this material is

(a) 1.416 eV   (b) 0.886 eV
(c) 0.854 eV   (d) 0.706 eV

Solution : (a)

$$E_G = \frac{1.24}{\lambda(\mu m)} eV = \frac{1.24}{0.87 \mu m} eV = 1.425\ eV$$

1.2.1 The Photon Nature of Light

Assume that an atom has been raised from the ground state to an excited level by electron bombardment. The mean life of an excited state ranges from 10^{-7} to 10^{-10} s, the excited electron returning to its previous state after the lapse of this time. In this transition, the atom must lose an amount of energy equal to the difference in energy between the two states that it has successively occupied, this energy appearing in the form of radiation. According to the postulates of Bohr, this energy is emitted in the form of a photon of light, the frequency of this radiation being given by Eq. (1.4), or the wavelength by Eq. (1.7). The term photon denotes an amount of radiate energy equal to the constant h times of the frequency.

1.3 Electronic Structure of the Elements

The inner-shell electrons are very strongly bound to an atom, and cannot be easily removed. That is, the electrons closest to the nucleus are the most tightly bound, and so have the lowest energy. Also, atoms for which the electrons exists in closed shells form very stable configurations. For example, the inert gases He, Ne, Ar, Kr and Xe all have either completely filled shells or, at least, completely filled subshells.

Carbon, silicon, germanium, and tin have the electronic configurations indicated in Table (1.1). Note that each of these elements has completely filled subshells except for the outermost p shell, which contains only two of the six possible electrons. Despite this similarity, carbon in crystalline form (diamond) is an insulator, silicon and germanium solids are semiconductors, and tin is a metal.

Element	Atomic Number	Configuration
C	6	$1s^2\ 2s^2\ 2p^2$
Si	14	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$
Ge	32	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$
Sn	50	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 5s^2\ 5p^2$

Table-1.1 : *Electronic configuration in Group IVA*

Example - 1.3   Atomic number of silicon is

(a) 12   (b) 13

(c) 14   (d) 15

Solution : (c)

From Table-1.1 atomic number of Silicon is 14.

1.4 The Energy-Band Theory of Crystals

X-ray and other studies reveal that most metals and semiconductors are crystalline in structure. A crystal consists of a space array of atoms or molecules (strictly speaking, ions) built up by regular repetition in three dimensions of some fundamental structural unit. The electronic energy levels discussed for a single free atom (as in a gas, where the atoms are sufficiently far apart not to exert any influence on one another) do not apply to the same atom in a crystal. When atoms form crystals it is found that the energy levels of the inner-shell electrons are not affected appreciably by the presence of the neighbouring atoms. However, the levels of the outer-shell electrons are changed considerably, since these electrons are shared by more than one atom in the crystal. The new energy levels of the outer electrons can be determined by means of quantum mechanics, and it is found that coupling between the outer-shell electrons of the atoms results in a band of closely spaced energy states instead of the widely separated energy levels of the isolated atom [Fig. (1.2)]. A qualitative discussion of this energy-band structure follows.
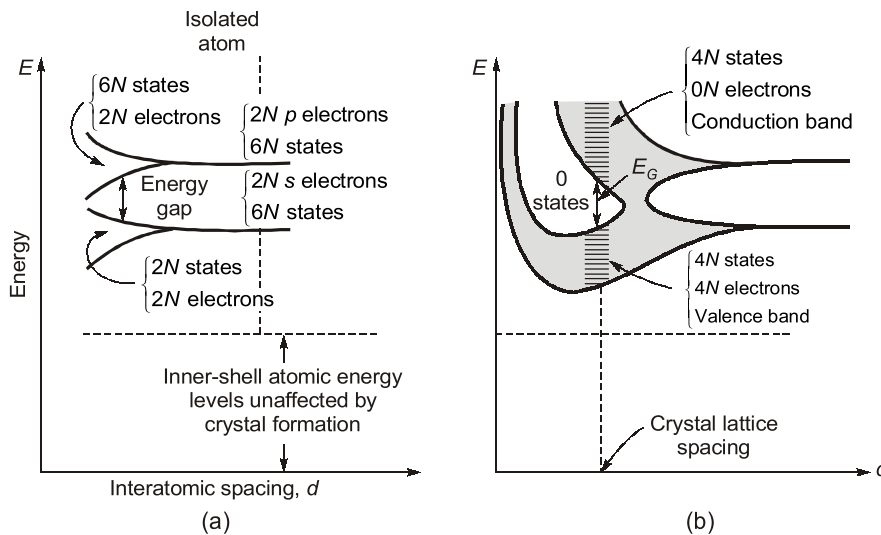
Figure-1.2 : *Illustrating how the energy levels of isolated atoms are split into energy bands when these atoms are brought into close proximity to form a crystal*

Consider a crystal consisting of N atoms of one of the elements in Table (1.1). Imagine that it is possible to vary the spacing between atoms without altering the type of fundamental crystal structure. If the atoms are so far apart that the integration between them is negligible, the energy levels will coincide with those of the isolated atom. The outer two subshells for each element in Table (1.1) contain two s electrons and two p electrons. Hence, if we ignore the inner-shell levels, then, as indicated to the extreme right in Fig. 1.2 (a), there are $2N$ electrons completely filling the $2N$ possible s levels, all at the same energy. Since the p atomic subshell has six possible states, our imaginary crystal of widely spaced atoms has $2N$ electrons, which fill only one-third of the $6N$ possible p states, all at the same level.

If we now decrease the interatomic spacing of our imaginary crystal (moving from right to left in Fig. 1.2 (a), an atom will exert an electric force on its neighbours. Because of this coupling between atoms, the atomic-wave functions overlap, and the crystal becomes an electronic system which must obey the Pauli exclusion principle. Hence the $2N$ degenerate s states must spread out in energy. The separation between levels is small, but since N is very large ($\sim 10^{23}$ cm^{-3}), the total spread between the minimum and maximum energy may be several electron volts if the interatomic distance is decreased sufficiently. This large number of discrete but closely spaced energy levels is called an **energy band**, and is indicated schematically by the lower shaded region in Fig. 1.2 (a). The $2N$ states in this band are completely filed with $2N$ electrons. Similarly, the upper shaded region in Fig. 1.2 (a) is a band of $6N$ states which has only $2N$ of its levels occupied by electrons.

Note that there is an energy gap (a forbidden band) between the two bands discussed above and that this gap decreases as the atomic spacing decreases. For small enough distance (not indicated in Fig. 1.2 (a) but shown in Fig. 1.2 (b) these bands will overlap. Under such circumstances the $6N$ upper states merge with the $2N$ lower states, giving a total of $8N$ levels, half of which are occupied by the $2N + 2N = 4N$ available electrons. At this spacing each atom has given up four electrons to the band; these electrons can no longer be said to orbit in s or p subshells of an isolated atom, but rather they belong to the crystal as a whole. In this sense the elements in Table (1.1) are tetravalent, since they contribute four electrons each to the crystal. The band these electrons occupy is called the **valence band**.

If the spacing between atoms is decreased below the distance at which the bands overlap, the interaction between atoms is indeed large. the energy-band structure then depends upon the orientation of the atoms relative to one another in space (the crystal structure) and upon the atomic number, which determines the electrical constitution of each atom. Solutions of Schrodinger's equation are complicated, and have been obtained approximately for only relatively few crystals. These solutions lead us to expect an energy-band diagram somewhat as pictured[4] in Fig. 1.2 (b). At the crystal-lattice spacing (the dashed vertical line), we find the valence band **filled** with $4N$ electrons separated by a forbidden band (no allowed energy states) of extent E_G from an **empty** band consisting of $4N$ additional states. This upper vacant band is called the **conduction band**.
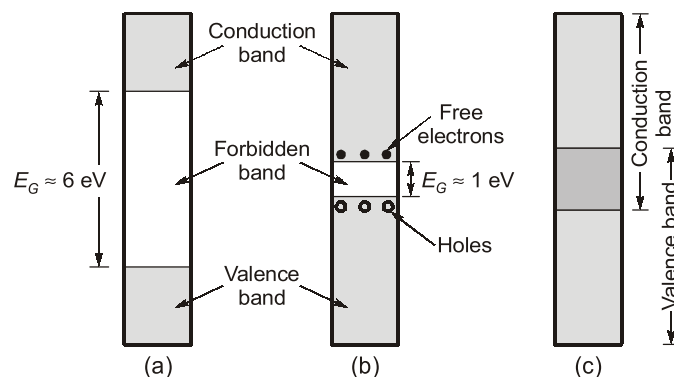
1.5   **Insulators, Semiconductors and Metals**

Figure-1.3 : *Simplified energy band diagrams of (a) insulator (b) semiconductor (c) conductor*

1.5.1 Insulators

- An insulating material has an energy band diagram as shown in Fig. 1.3 (a).
- It has a very wide forbidden-energy gap ($\simeq 6$ eV) separating the filled valence band from the vacant conduction band. Because of this, it is practically impossible for an electron in the valence band to jump the gap, reach the conduction band.
- At room temperature, an insulator does not conduct. However it may conduct if its temperature is very high or if a high voltage is applied across it. This is termed as the **breakdown of the insulator.**
- **Example:** diamond.

1.5.2 Semiconductors

- A semiconductor has an energy-band gap as shown in Fig. 1.3 (b).
- At 0°K semiconductor materials have the same structure as insulators except the difference in the size of the band gap E_G, which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.
- The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amount of thermal or optical energy.
- The difference between semiconductors and insulators is that the conductivity of semiconductors can increase greatly by thermal or optical energy.
- **Example:** Ge and Si.

1.5.3 Metals

- There is no forbidden energy gap between the valence and conduction bands. The two bands actually overlap as shown in Fig. 1.3 (c).
- Without supplying any additional energy such as heat or light, a metal already contains a large number of free electrons and that is why it works as a good conductor.
- **Example:** Al, Cu etc.

Remember	Conduction band electrons can move along sea of atoms present in the specimen under consideration while the valence band electrons (restrained electrons) are bound to parent atom. These conduction band electrons are known as *free electrons*.

NOTE	Since the band-gap energy of a crystal is a function of interatomic spacing, it is not surprising that E_G depends somewhat on temperature. It has been determined experimentally that E_G for silicon decrease with temperature at the rate of 3.60×10^{-4} eV/°K. Hence, for silicon, $\quad E_G(T) = 1.21 - 3.60 \times 10^{-4}\,T$ and at room temperature (300°K), $E_G = 1.1$ eV Similarly, for germanium, $\quad E_G(T) = 0.785 - 2.23 \times 10^{-4}\,T$ and at room temperature, $\quad E_G = 0.72$ eV

Example - 1.4	The bandgap of Silicon at room temperature is

(a) 1.3 eV $\qquad\qquad\qquad\qquad$ (b) 0.7 eV

(c) 1.1 eV $\qquad\qquad\qquad\qquad$ (d) 1.4 eV

Solution : (c)

$$E_G(T) = 1.21 - 3.60 \times 10^{-4}\,T$$

At $T = 300$ °K, $\qquad E_G = 1.1$ eV