# Semiconductors, Materials and Junction Diodes

CHAPTER 2

## 2.1 CLASSIFICATION OF SOLIDS

depend on

بيتنقل اليها

The solid materials are classified into three groups from the consideration of their current carrying capabilities: *conductors*, *insulators* and *semiconductors*. Conductors have an abundance of free electrons that act as charge carriers, which means that they have high conductivity. An insulator on the other hand, has hardly any free electrons and offers very low level of conductivity. A semiconductor is a material that has a conductivity level somewhere between the extremes of an insulator and a conductor. The term *resistivity* (inverse of *conductivity*) is often used when comparing the resistance levels of materials. Typical resistivity values for three broad categories of materials are shown in Table 2.1.

مثالى عام الاصناف

**Table 2.1** Typical Electrical Resistivity Values of Different Materials (at 20°C in Ω cm)

| Conductor | Semiconductor | Insulator |
|---|---|---|
| Copper (Cu) ~ $1.7 \times 10^{-6}$ | Silicon (Si) ~ $50 \times 10^3$ | Mica ~ $7 \times 10^{12}$ |
| Silver (Ag) ~ $1.6 \times 10^{-6}$ | Germanium (Ge) ~ 50 | Glass ~ $10^8 - 10^9$ |
| Aluminium (Al) ~ $2.8 \times 10^{-6}$ | Indium–Antimonide(InSb) ~ 200 | Diamond ~ $10^{12}$ |
| Iron (Fe) ~ $10 \times 10^{-6}$ | $E_g = 1.1 — 2.1$ eV. | $E_g = 5.8$c |
| Nichrome(NiCr) ~ $100 \times 10^{-6}$ | V.B — C.B | |

$E_g = 0$

It is observed that at 20°C, semiconductors have resistivity lying between that of metals and insulators. But, at a very low temperature (nearly absolute zero), a semiconductor behaves as an insulator. It is noted that semiconductors in very pure form have negative temperature coefficient of resistance, i.e. their resistivity decreases (or conductivity increases) rapidly with the increase of temperature. In other words, the number of charge carriers increases rapidly with temperature. Conductors, quite contrary to the above, have positive temperature coefficient of resistance. Semiconductors have the special feature of having two types of charge carriers: *electrons* and *holes*. 'Holes' are absence of 'electrons' in covalent bonds and act equivalently as positive charge carriers. Further, semiconductors have the unique property such that their conductivity increases by several orders of magnitude even by minute amount of doping with certain impurities. In fact, this property of semiconductor is exploited to develop electronic devices. Among the semiconductor materials, Silicon (Si), Germanium (Ge) and Gallium Arsenide (GaAs) have received the broadest range of interest in the development of semiconductor devices. The fact that characteristics of

عكس

تطور

تنظيم البنيوي

شكل ملحوظ

semiconductors can be significantly altered through the application of heat or light. It has opened an area of application of these materials as heat and light sensitive devices. متعدد التبلور

Solids may be classified by structural organization into *crystalline*, *polycrystalline*, and *amorphous* types. An amorphous solid does not have a well-defined structure; in fact, it is distinguished by its formlessness as shown in Fig. 2.1(a). In a polycrystalline solid, as in Fig. 2.1(b), there are many small regions, each having a well-organized structure but differing from its neighbouring regions. Such a material can be produced inexpensively and is used extensively in microelectronics. In crystalline solid, atoms are arranged in an orderly array, Fig. 2.1(c), that defines a periodic structure (i.e. continually repeats itself) called the *lattice*. It is possible to

غير متبلور

بلا شكل محدد

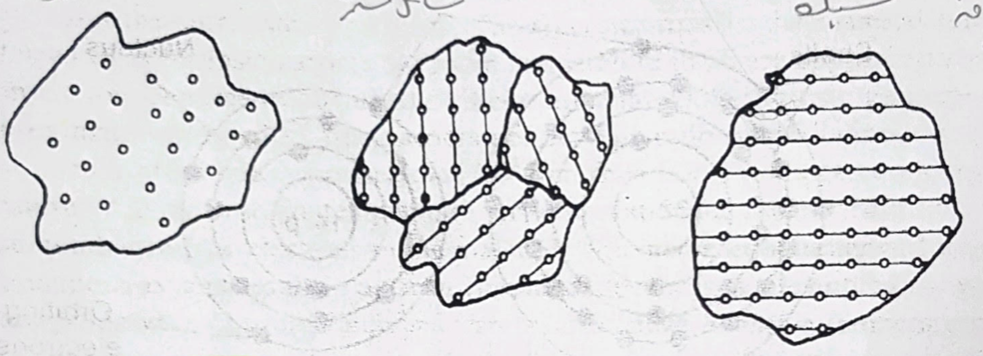
ضخم

دوري

بشكل مستمر

شبكة

على نطاق واسع



(a) Amorphous (b) Polycrystalline (c) Crystalline

**Fig. 2.1** Classification of solids based on structural organization.

specify a unit cell which, when repeating itself, produces the *crystalline* solid. For Ge and Si, the crystal has the three-dimensional diamond structure as shown in Fig. 2.2. Any material solely composed by repeating crystal structures of the same kind is called a *single-crystal* structure. For semiconductor materials of practical application in the electronics field, this single-crystal feature exists, and in addition, the periodicity of the structure does not change significantly with the addition of controlled amount of impurities in the doping process.

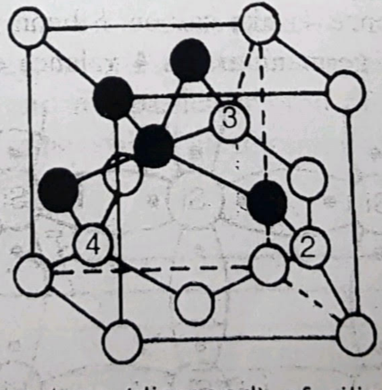
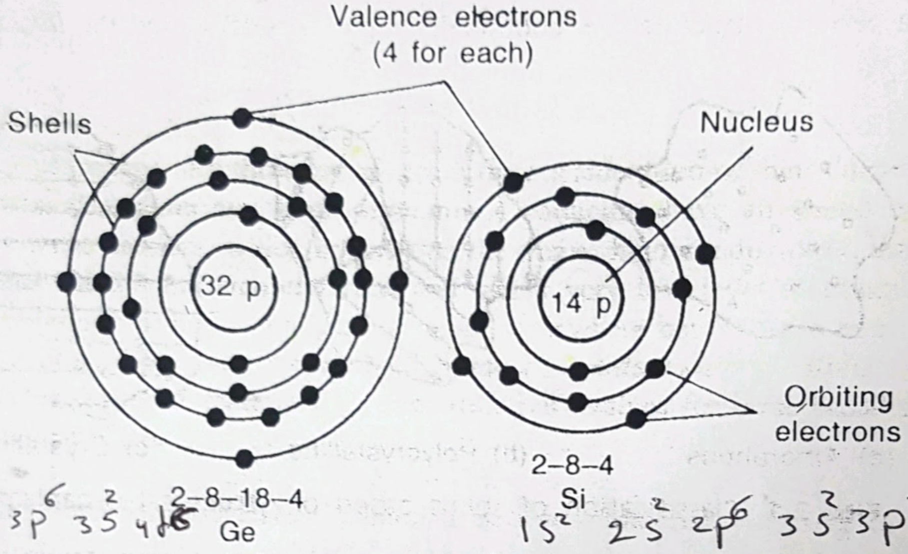


**Fig. 2.2** Crystal structure (diamond) of silicon and germanium.

## 2.2 ATOMIC STRUCTURE AND ENERGY LEVELS

The most fundamental unit of all matter is the *atom* consisting of three basic particles; the *electron*, the *proton* and the *neutron*. Neutrons do not carry charge while protons and electrons are respectively positively and negatively charged. An atom contains the same number of electrons and protons. The atoms of various elements differ in number of sub-atomic particles, i.e. electrons, protons and neutrons they contain. In the atomic lattice, neutron and proton are the heaviest particles, which make the core of the atom, called *nucleus*. Electrons revolve around the nucleus in fixed *orbits*. The orbits are denoted by principal quantum numbers or K, L, M, N shells. Each orbit represents an energy level. Electrons are arranged in order of $2n^2$, where $n$ is the orbit number. For example, first shell can accommodate 2 electrons, second can 8, third can 18, and so on. The Bohr models of the two common semiconductors, germanium and silicon, are shown in Fig. 2.3. The figure indicates that germanium atom has 32 orbiting electrons, while silicon has 14 orbiting electrons. In each case, there are 4 electrons in the outermost (valence) shell. Valence electrons are the electrons in the outermost shell. These electrons are involved in chemical bonding leading to chemical reactions. The potential (ionization potential) required to remove any of these 4 electrons is lower than that required for any other electron in the structure. In a pure Ge or Si crystal, these 4 valence electrons are bonded to 4 adjoining atoms, as shown in Fig. 2.4. Both Si and Ge are tetravalent atoms (valence 4) like carbon. Silicon is lighter than germanium and has 4 electrons in 3s, 3p states, while germanium has 4 valence electrons in 4s, 4p states.



$s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3s^2\ 4d6$

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$.

Fig. 2.3 Atomic structure of silicon and germanium (Bohr model).

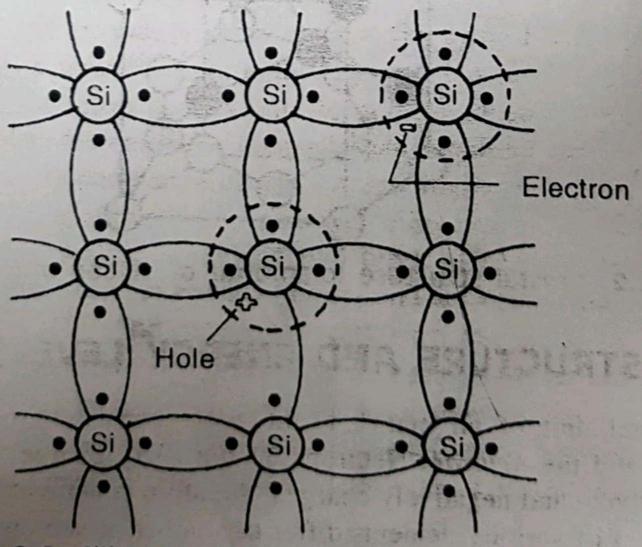


Fig. 2.4 Silicon crystal with covalent bonding.

مرتبط الارتباط

Atoms are linked together to form molecules of matter. This linkage or interconnection, called *bonding*, takes place through the interaction of valence electrons. The force that binds these atoms is electrostatic in nature. A bonding of atom, strengthened by the sharing of electrons, is called *covalent* bonding. The concept of sharing is different from the ionic bonding due to gaining or losing valence electron in adjacent atoms. Moreover, there is no ion formation. Although the covalent bond will result in stronger bond between the valence electrons and their parent atom, it is still possible for the valence electrons to absorb sufficient kinetic energy from natural causes to break the covalent bond and assume the 'free' state. The term 'free' means that their motion is quite sensitive to applied electric fields established by voltage sources or any difference in potential. These natural causes include effects such as light energy in the form of photons and thermal energy from the surrounding medium. The free electrons in the material due to natural causes are referred to as intrinsic carriers. At room temperature there are approximately $1.5 \times 10^{10}$ free carriers in a cubic centimetre of intrinsic silicon material while intrinsic germanium material will have approximately $2.5 \times 10^{13}$ free carriers per cc. The ratio of the number of free carriers in germanium to that of silicon is greater than $10^3$ and thus Ge is a better conductor than Si at room temperature. An increase in temperature of a semiconductor can result in a substantial increase in the number of free electrons in the material. The increased number of free carriers will increase the conductivity and result in a lower resistance level. Thus Ge and Si show a reduction in resistance with increase in temperature and are said to have *negative* temperature coefficient of resistivity. In contrast, the number of carriers in a metal will not increase significantly with temperature, but the vibration pattern of the atoms about relatively fixed locations will make it increasingly difficult for electrons to pass through. An increase in temperature results in an increased resistance level and therefore metals will have positive temperature coefficient.

### 2.2.1 Energy Levels

As shown in Fig. 2.5, there are discrete energy levels associated with each orbiting electron in an isolated atomic structure. Each material will, in fact, have its own set of permissible energy levels for the electrons in its atomic structure. There are gaps between the discrete energy levels in which no electrons in the isolated atomic structure can appear. Atoms, however, do not exist in isolation but are seen in large groups crowded together to form a solid by arranging themselves in a regular three-dimensional array, a solid crystal is formed. There is an interaction between atoms that will result in the electrons in a particular orbit of one atom having slightly different energy levels from electrons in the same orbit of an adjoining atom. No two electrons share exactly

متجاور

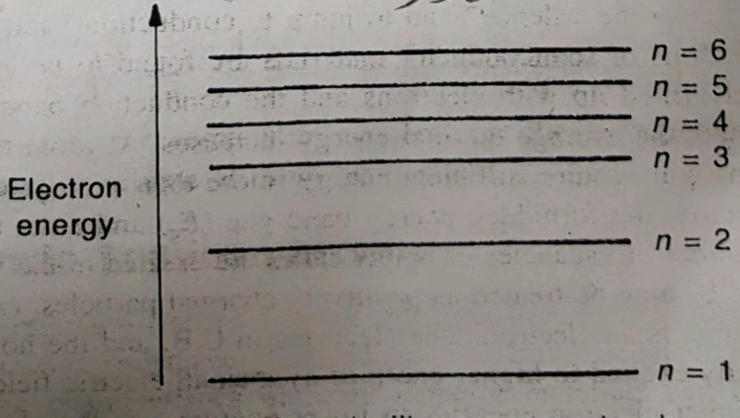


**Fig. 2.5** Different silicon energy levels.

the same quantum number and, therefore, the energy of any two electrons cannot be the same. Each shell is therefore divided into subshells, each subshell having a different energy level. The net result is the formation of *energy bands*. Each 'band' really consists of a very large number of discrete energy levels, which are very closely spaced. These bands may be thought of as continuous. These energy bands (called *allowed bands*) are separated by *forbidden* energy gaps, i.e. no electron can have any energy value within *forbidden bands*. Figure 2.6 shows the theoretical curve of the energy band of diamond lattice (Si, Ge) as a function of atomic spacing. When atomic spacing is sufficiently wide, interaction between atoms is negligible and energy levels are similar to isolated atoms.

حزم

(الطا

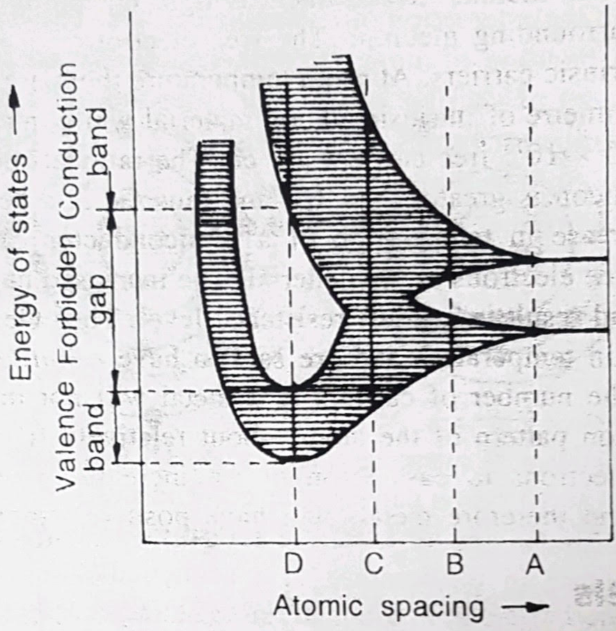


**Fig. 2.6** Energy band of diamond lattice as a function of atomic spacing.

It may be noted that the energy associated with each electron is measured in electron volts (eV). It is defined as the amount of energy gained or lost when an electron falls through or moves against a potential difference of one volt. In term of joules ($W = qV$), 1 eV = $1.6 \times 10^{-19}$ J.

In a solid crystal, the energy band, called *valence band*, originated from the shells occupied by valence electrons in a single atom (3s, 3p for Si and 4s, 4p for Ge) is separated from another higher energy band, called *conduction band* in the case of a semiconductor. The gap between these two bands is called *forbidden* energy gap ($E_g$). Thus $E_g$ is the amount of energy that should be imparted to the electron in the valence band to jump to conduction band. At 0 K or absolute zero, all the valence electrons of semiconductor materials are found to be locked in the valence band which is completely filled up with electrons and the conduction band is perfectly empty. If the temperature is raised, the average thermal energy increases. At room temperature (300 K), some of valence electrons will acquire sufficient energy (more than average energy, 0.026 eV) to leave the valence band, cross the forbidden energy band gap ($E_g$) and enter the conduction band (C.B.). Thus an equal number of vacancies or empty states are created in the valence band (V.B.). These vacancies in the V.B. may be treated as positively charged particles, called 'holes', having the same quantity of charge as an electron. The electrons in C.B. and the holes in V.B. are *free*, because they may be easily excited to higher energies by a small electric field or thermal energy. The holes move from higher electron energies to lower energies, as the electrons from a lower energy combine with holes or fill-up vacancies, subsequently creating new vacancies or holes.

يُعطى

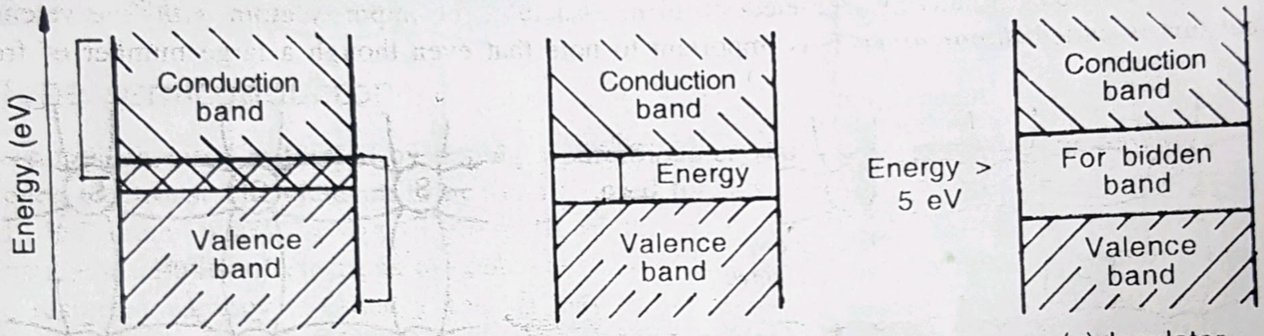
يكتسب

فجوات

These free charge carriers (electrons in C.B. and holes in V.B.) carry electrical current. The energy band diagrams of conductor, semiconductor and insulator are shown in Fig. 2.7. For conductors (metals), the C.B. and V.B. overlap each other. Refer to Fig. 2.7(a), $E_g = 0$. So, a large number of valence electrons ($\approx 10^{22}$ per cm$^3$) are available for conduction at room temperature to sustain a heavy flow of charge, or current at room temperature. Increasing temperature, electrons face more obstacle to their movement because of increased atomic vibrations. For insulators, $E_g >> kT$ ($E_g \approx 4$–$8$ eV), very few electron-hole pairs may be created by thermal process. Refer to Fig. 2.7(c). Thus, insulators or dielectrics are extremely poor conductors of electricity. For semiconductors in pure, crystalline form, $E_g$ lies in the range 0.1–3 eV. Refer to Fig. 2.7(b). Thus, appreciable number of electron-hole pairs is created by thermal process. Increasing temperature causes creation of more

عائق

عازل



(a) Conductor (b) Semiconductor (c) Insulator

$E_g = 0$

$E_g >> kT$

**Fig. 2.7** Energy band diagrams.

$E_g \simeq 0.1 - 3$ eV

$E_g = 4 - 8$ e

electron-hole pairs, hence resistivity falls. The number of electrons in C.B. or holes in V.B. per unit volume in an ideally pure and perfect semiconductor crystal is called *intrinsic carrier concentration*. Table 2.2 indicates $E_g$ values and intrinsic carrier concentration of some important semiconductor materials, at room temperature.

**Table 2.2** Properties of Some Useful Semiconductors

| Materials | Band gap ($E_g$) (in eV) | Intrinsic concentration ($T$ = 300 K) (per cm$^3$) |
|---|---|---|
| Ge | 0.67 | $10^{13}$ |
| Si | 1.12 | $10^{10}$ |
| GaAs | 1.42 | $10^{6}$ |

تقريباً

The obviously lower $E_g$ for germanium accounts for the increased number of carriers in that material as compared to silicon at room temperature.

## 2.2.2 Extrinsic Semiconductors

Pure silicon or germanium (intrinsic semiconductor) has little use except in the manufacture of heat and light sensitive resistance. The process of adding impurity to a pure semiconductor is called *doping*. The characteristics of semiconductor materials can be significantly altered by doping impurity atoms into relatively pure semiconductor. The added impurity is called *dopant*