Unit – 4: Semiconductor Physics

Importance of Semiconductor Physics in Engineering

Semiconductor physics is a crucial discipline in modern engineering, under pinning the design and development of electronic devices, computing systems, energy solutions, medical devices, and aerospace technologies. Its significance extends to electronics, electrical, computer, and materials science engineering, where understanding semiconductor physics is essential for creating innovative solutions. By studying semiconductor physics, engineering students gain a fundamental grasp of electronic device operation, including transistors, diodes, and integrated circuits. They learn to optimize device performance, select and develop materials, and contribute to emerging fields like quantum computing, nanotechnology, and renewable energy. Key concepts include band gap energy, carrier concentration, mobility, p-n junctions, and optoelectronic devices. Mastering semiconductor physics enables engineers to drive advancements in various industries, from consumer electronics to healthcare and energy. Furthermore, it fosters problem-solving skills, interdisciplinary connections, and career opportunities in fields like device engineering, materials science, and research and development. As technology continues to evolve, proficiency in semiconductor physics becomes increasingly vital for engineers to stay at the forefront of innovation.

Subtopics in Unit – 3

Semiconductor Physics	**4.1. Introduction to Semiconductor Physics** **4.2. Band theory of Solids** *4.2.1. Classification of Solids* **4.3. Types of Semiconductors** *4.3.1. Intrinsic Semiconductors* *4.3.2. Extrinsic Semiconductors* **4.4. Conductivity of Conductors and Semiconductors in terms of Mobility** *4.4.1. Conductivity of Conductors* *4.4.2. Conductivity of Semiconductors* **4.5. Fermi Dirac Distribution Function.** **4.5.1. Position of Fermi level in intrinsic and extrinsic semiconductor** **4.6. Working of P-N Junction Diode on the Basis of Energy Band Diagram** *4.6.1. p-n Junction Diode* *4.6.2. Energy Band structure of p-n Junction Diode* **4.7. Construction and Working of Solar Cell** *4.7.1. Solar Cell* *4.7.2. Applications of Solar Cells* *4.7.3. Construction of a Solar Cell* *4.7.4. Working of a Solar Cell* **4.8. Wide Band Gap Semiconductor**

Semiconductor Physics

4.1 Introduction to Semiconductor Physics

Semiconductor physics is a critical field that bridges the gap between insulators and conductors, enabling the development of modern electronic devices. Semiconductors, such as silicon and germanium, exhibit unique electrical properties that can be manipulated through doping and temperature variations, making them essential for a wide range of applications, from diodes and transistors to photovoltaic cells. Understanding the behavior of charge carriers within these materials—specifically, the mechanisms of electron mobility and the significance of the forbidden band gap—forms the foundation of semiconductor technology. As we delve into the principles of semiconductor physics, we will explore the essential concepts of energy band structures, carrier dynamics, and the impact of impurities, which collectively contribute to the functionality and innovation of contemporary electronic systems.

4.2 Band Theory of Solids

In 1928, Felix Bloch developed zone theory to describe the behaviour of electrons in the periodic potential created by a crystal lattice, which is commonly referred to as the band theory of solids. An isolated atom has discrete energy levels. When two identical atoms are far apart, the energy levels of each atom remain unaffected by the other. However, as the atoms are brought closer together and form a tightly packed structure, they begin to interact more strongly due to their proximity. As two atoms come close, one energy level splits into two. Similarly, when three atoms approach, the original level divides into three levels, and four atoms yield four levels, and so forth. In general, N interacting atoms cause a single energy level to split into N levels.

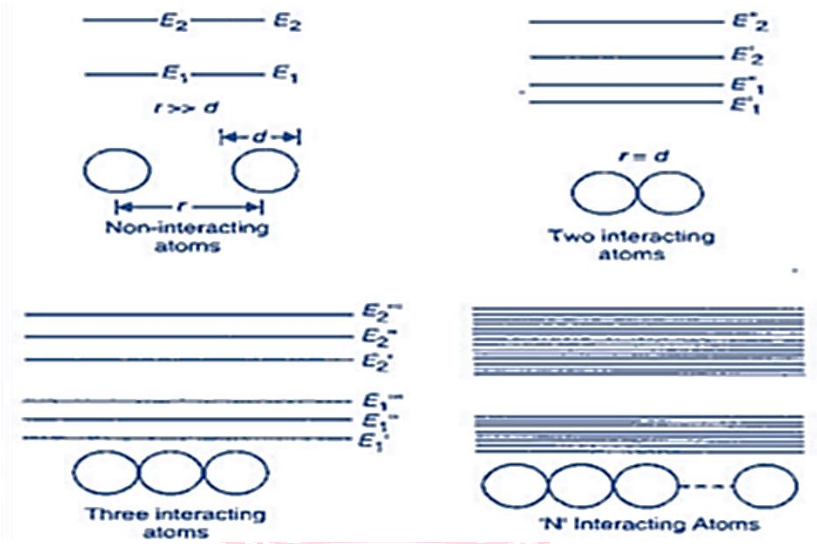

Figure 4.1. Band theory of solids.[1]

Therefore,

- The process by which a single energy level transforms into two or more distinct energy levels is referred to as energy level splitting.
- The numerous energy levels resulting from this splitting are closely spaced of the order of 10^{-28} eV, creating a continuum known as an energy band.
- The inner shell electrons are not affected significantly due to presence of neighboring atoms.
- The electronic configuration of group IV elements show that the two outermost subshells are the *s* and *p* subshells.
- The two subshells contain 2 electrons each are shown in table 4.1.

Table 4.1. Electronic configuration of group IV elements.

Element	Atomic Number	Electronic 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	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 5s^2\ 5p^2$

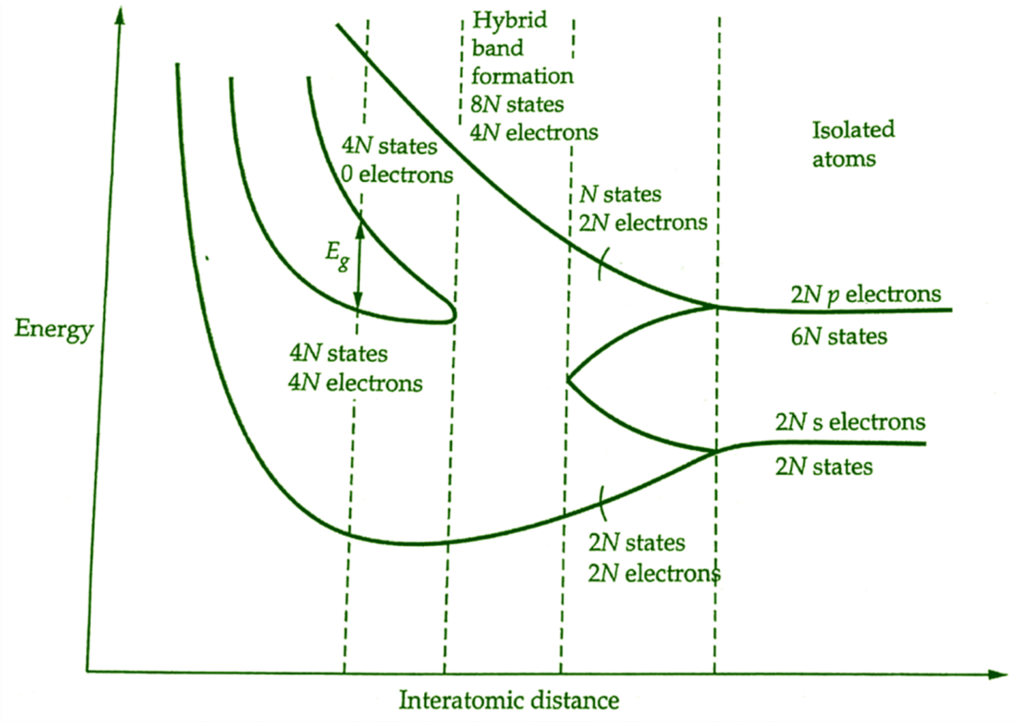

Figure 4.2. Splitting of energy levels as a function of interatomic distance.[1]

Figure 4.2 illustrates the splitting of energy levels as a function of interatomic distance and the depth of energy levels in an atom. When atoms are far apart, inter-electron interactions are minimal. Consequently:

- All atoms have identical energy levels for outermost 's' and 'p' subshells.
- The 's' subshell can accommodate 2N electrons in 2N available quantum states.
- The 'p' subshell can accommodate 2N electrons in 6N available quantum states.

As atoms draw closer, their energy levels begin to split due to atomic interactions, resulting in the formation of bands corresponding to different energy levels. This splitting effect intensifies with decreasing interatomic distance. Although the energy difference between adjacent levels within an energy band is very small, the total spread of the band is substantial due to the large number of atoms (~ 10^{23} atoms/cm^3). At smaller interatomic distances, energy bands expand and overlap extensively. The s-p hybrid band comprises 8N available states, with 4N occupied by electrons. This phenomenon signifies the transition of electrons from atomic 's' and 'p' subshells to a collective crystal-wide energy state. Consequently, each atom contributes four electrons to the hybrid band. Further reducing interatomic distance triggers the division of hybrid band into two separate energy bands. Figure 4.3 gives an illustrated picture of this phenomenon.

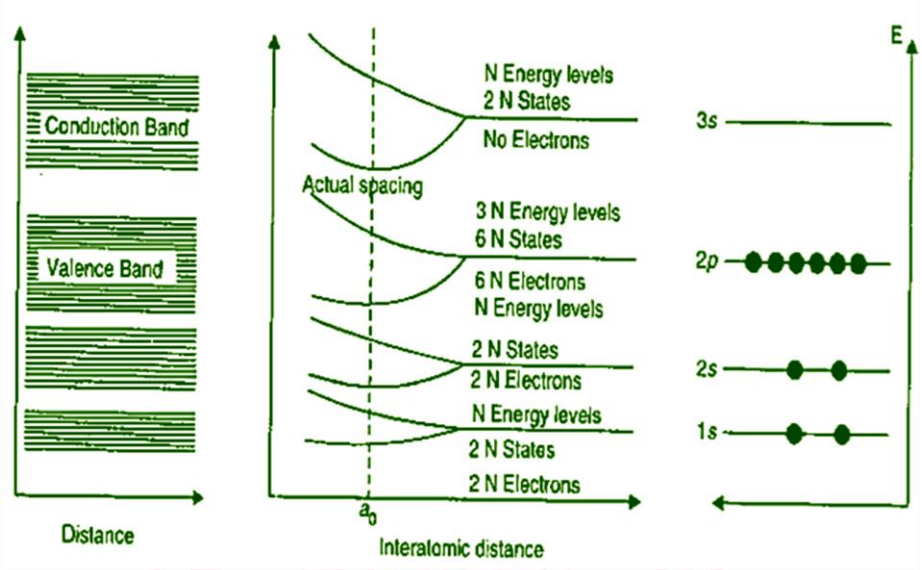

Figure 4.3. Band theory of solids in terms of interatomic distance.[1]

The energy level splitting in an atom also depends on the position of the energy level. Inner levels experience less splitting, forming narrow bands that remain fully occupied. As a result, these inner levels do not contribute to electrical conduction. In contrast, outer levels exhibit greater splitting, forming wider bands. Electrons occupy these bands in a sequential manner, starting from the lowest energy level and filling upwards in ascending order.

Valence Band: This is where electrons are bound to their atoms and don't contribute to electric current.

Conduction Band: Above the valence band, the conduction band consists of energy levels where electrons can move freely. This mobility is what allows for charge flow when an external voltage is applied.

Forbidden Band: The gap between the valence band and the conduction band is called the forbidden band. This is the energy required for an electron to transition from the valence band to the conduction band—essentially, the energy needed for a valence electron to become a free electron. For reference, 1 eV is equal to 1.6×10^{-19} J.

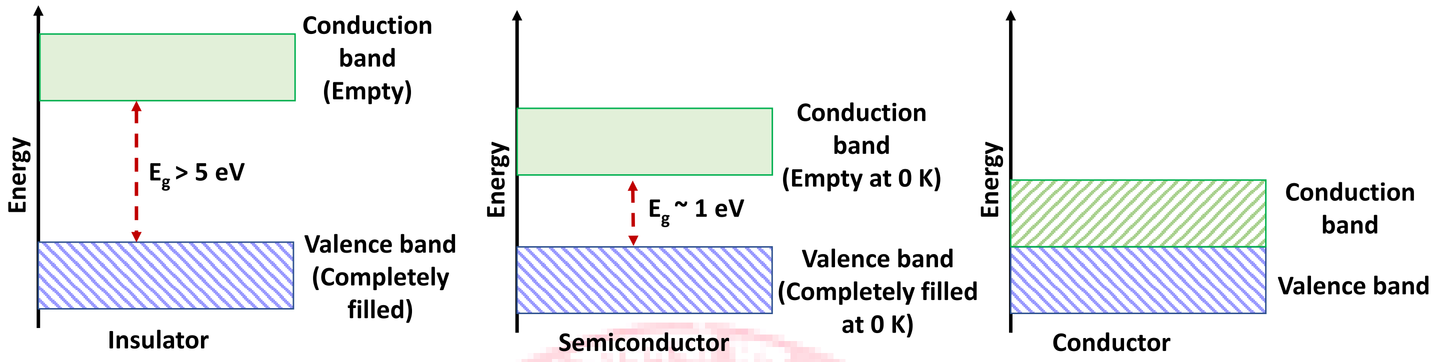

Figure 4.3. Energy band diagrams of insulator, semiconductor and conductor

4.2.1 Classification of Solid

All materials in nature are categorized as insulators, semiconductors, or conductors based on their band structure and electrical conductivity.

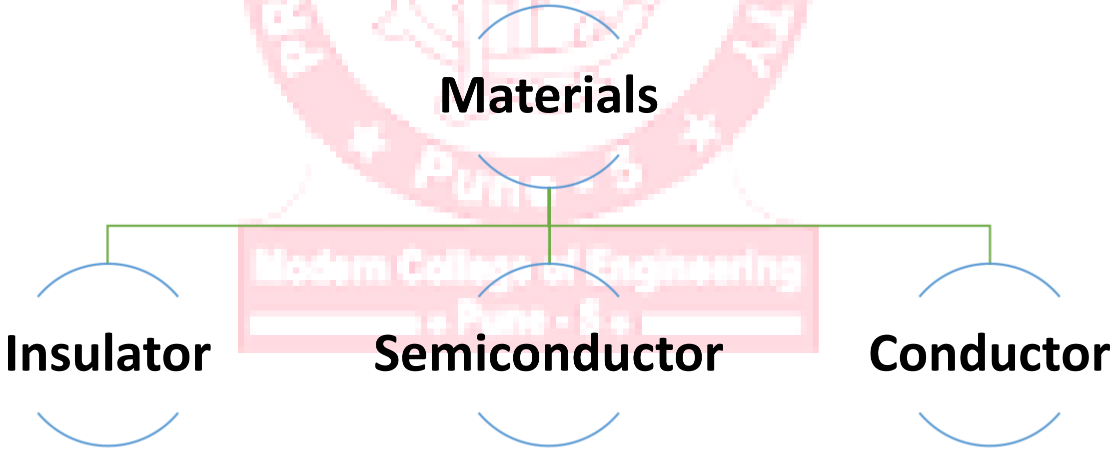

Figure 4.4. Categorization of materials based on their electrical conductivity.

Insulator: An insulator is a material that shows very low or negligible conductivity when voltage is applied. Common examples include paper, mica, glass, and quartz. Typically, the resistivity of insulators ranges from 10^{10} to 10^{12} Ω-cm. Let's take a closer look at the energy band structure of an insulator, which is illustrated in Figure 4.4. This band structure defines the range of energy levels that electrons can occupy.

In the case of insulators, as shown in Figure 4.4, the forbidden band gap is quite large, often greater than 5 eV. Because of this significant gap, very few electrons are present in the conduction band, resulting in poor conductivity. Even when the temperature increases or an electric field is applied, it's usually not enough to promote electrons from the valence band to the conduction band.

Conductor: A conductor is a material that allows a substantial flow of electric charge when a voltage is applied across its terminals, meaning it has very high conductivity. Common examples include copper, aluminium, silver, and gold. The resistivity of conductors typically ranges from 10^{-4} to 10^{-6} Ω-cm. In conductors, the valence and conduction bands overlap, as shown in Figure 4.4, resulting in no energy gap for electrons to transition between these bands. This means that free electrons are present in the conduction band even at absolute zero temperature (0 K). Consequently, when an electric field is applied at room temperature, a significant current can flow through the conductor.

Semiconductor: A semiconductor is a material with conductivity that falls between that of insulators and conductors. Its resistivity typically ranges from 10 to 10^4 Ω-cm. Silicon (Si, atomic number 14) and germanium (Ge, atomic number 32) are two of the most widely used semiconductors, both featuring four valence electrons. The forbidden band gap for semiconductors is around 1 eV. For instance, the band gap energies for silicon, germanium, and gallium arsenide (GaAs) are 1.21 eV, 0.785 eV, and 1.42 eV, respectively, at absolute zero temperature (0 K). At 0 K and low temperatures, valence band electrons lack the energy needed to transition to the conduction band, making semiconductors behave like insulators. However, as the temperature rises, many valence electrons gain enough energy to leave the valence band, cross the forbidden band gap, and enter the conduction band. These electrons become free to move under the influence of an electric field. At room temperature, there are enough electrons in the conduction band, allowing the semiconductor to conduct some current. Thus, semiconductors are said to exhibit a ***negative temperature coefficient***, meaning their conductivity increases and resistivity decreases with increase in temperatures.

4.3 Types of Semiconductors

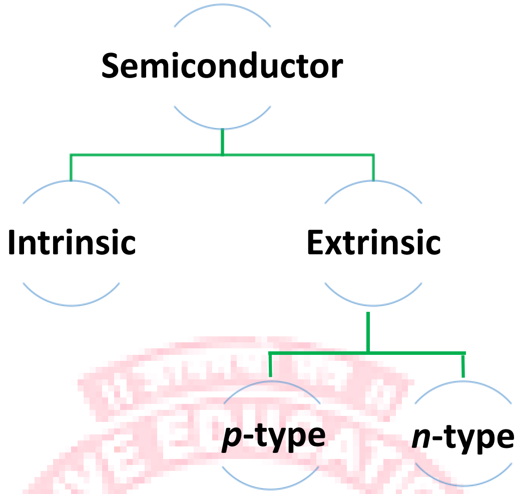

Figure 4.5. Types of semiconductors.

4.3.1 Intrinsic Semiconductor:

Semiconductors in their chemically pure (all atoms are identical) form are known as intrinsic semiconductors. Conduction in these materials is driven by thermal energy or crystal imperfections. Notable intrinsic semiconductors include IV group elements of the periodic table, e.g., Si, Ge, GaAs, and InSb. Semiconductors are characterized by a narrow energy gap separating the conduction and valence bands in their energy band diagram. At absolute zero (0K), intrinsic semiconductors behave as a perfect insulator.

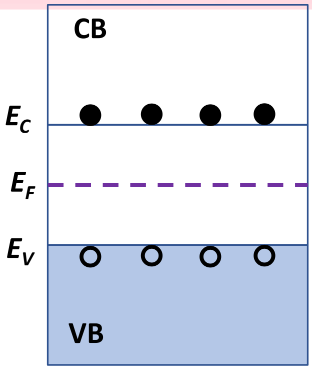

Figure 4.6. Energy band diagram of an intrinsic semiconductor.

4.3.2 Extrinsic Semiconductor:

Intrinsic semiconductors have limited practical applications due to their low conductivity at room temperature, carrying only minimal electric current. However, their current-carrying capacity can be substantially enhanced by introducing trace amounts of selected impurities. This process is called doping

Therefore, an extrinsic semiconductor is a type of semiconductor material that has been intentionally doped with impurities to modify its electrical properties. These dopants may replace some of the original atoms in the crystal lattice.

There are two types of extrinsic semiconductor:

- N-type semiconductor: Doped with donor impurities (e.g., Phosphorus, Arsenic) that add excess electrons to the material, increasing its conductivity.
- P-type semiconductor: Doped with acceptor impurities (e.g., Boron, Gallium) that create holes (positive charge carriers), also increasing conductivity.

n-type Semiconductor:

Doping a pure semiconductor with pentavalent elements such as Phosphorus, Arsenic, or Antimony results in an n-type semiconductor, characterized by an excess of electrons. Pentavalent impurities, like phosphorous, possess five valence electrons. In an n-type semiconductor (Figure 4.7), four of these electrons form covalent bonds with neighboring intrinsic semiconductor atoms, while the fifth electron remains loosely bound to the impurity atom. The loosely bound electron in an n-type semiconductor can be easily excited from the valence band to the conduction band by applying an electric field or increasing thermal energy. Notably, the energy required to detach this electron from the impurity atom is extremely low, approximately 0.01 eV for Germanium (Ge) and 0.05 eV for Silicon (Si).

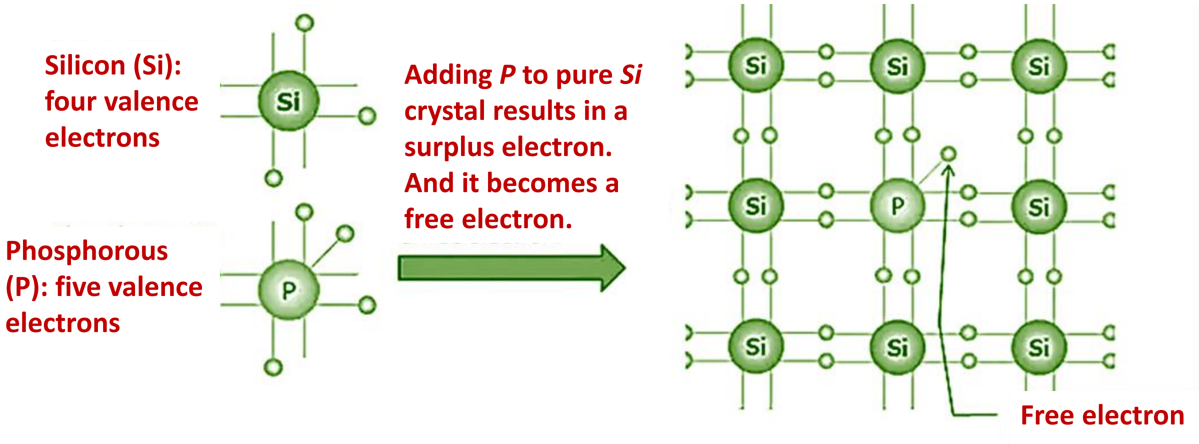

Figure 4.7. Crystal structure of an n-type semiconductor. The free electron is the carrier of an n-type semiconductor.[2]

Doping introduces a discrete energy level, known as the donor energy level (E_D), within the forbidden band gap, positioned slightly below the conduction band, as shown in Figure 4.8.

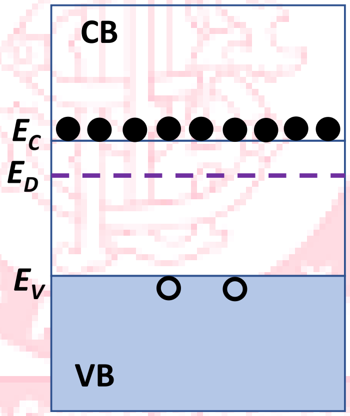

Figure 4.8. Energy band diagram of an n-type extrinsic semiconductor.

<u>p-type Semiconductor:</u>

When a trivalent impurity, such as Boron, Gallium, or Indium, is added to a semiconductor, it becomes a p-type semiconductor (Figure 4.9). The trivalent atom's three valence electrons form three covalent bonds with neighboring atoms, leaving a vacancy, or "hole," that can accept an electron. Each trivalent atom generates one hole, significantly increasing their number in the valence band. Concurrently, electron concentration decreases due to enhanced recombination caused by the additional holes.

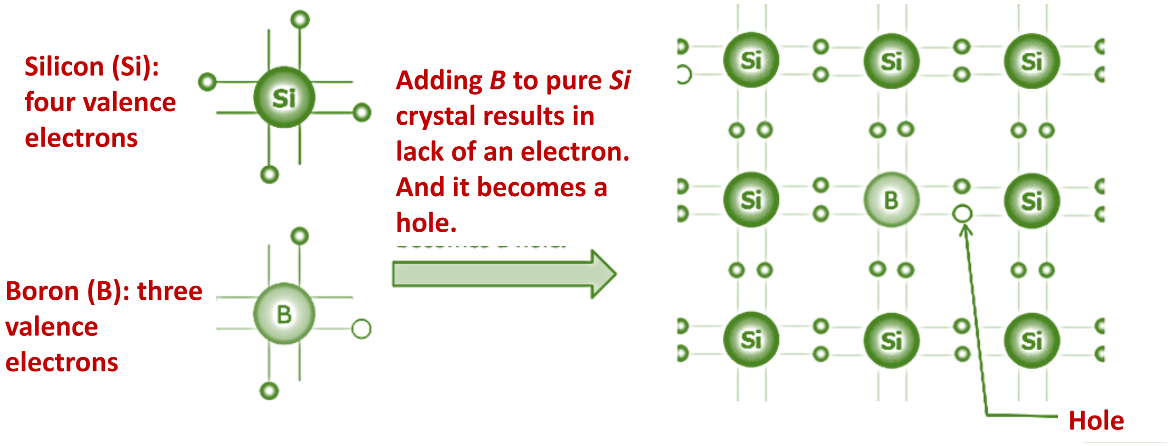

Figure 4.9. Crystal structure of a p-type semiconductor. The hole is the carrier of a p-type semiconductor.[2]

Doping introduces a discrete energy level, known as the acceptor energy level (E_A), within the forbidden band gap, situated approximately 0.01 eV above the valence band. The acceptor level represents the ground state energy of a hole, as shown in Figure 4.10.

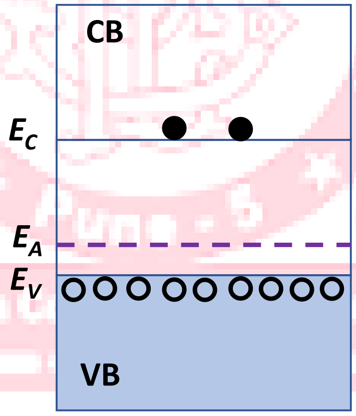

Figure 4.10. Energy band diagram of a p-type extrinsic semiconductor.

Numericals: Example and Practice Problems: Band gap energy

Worked-out Problem:

Example: Calculate the band gap energy in silicon given that it is transparent to radiation of wavelength greater than 11000 Å. (Ans: 1.13 eV)

Sol: Given:

$h= 6.63\times10^{-34}$Js

$c =3x10^{8}$ m/s

alternatively, hc= 1240 ev.nm

λ=11000 Å = 11000×10^{-10} m

Formula:

$E_g= hc/\lambda$

$\therefore E_g= 1.13$ eV

Problems:

4.1. Calculate the wavelength at which germanium starts to absorb light. Eg in Ge is 0.7 eV. (Ans: 17760 Å)

4.2. Calculate the band gap energy in Germanium. Given that it is transparent to radiation of wavelength greater than 17760 Å. (Ans: 0.695 eV).

4.4 Conductivity of Conductors and Semiconductors in terms of Mobility

4.4.1 Conductivity of Conductors:

Resistivity, or specific resistance, is a measure of the inherent resistance of a material, defined as the resistance of a unit-length conductor with a unit cross-sectional area.

$$R = \rho\frac{l}{A}$$

Where,

$$\rho = Resistivity$$

$$l = Length\ of\ conductor$$

$$A = Cross - sectional\ area$$

Conductivity is defined as the reciprocal of resistivity:

$$\sigma = \frac{1}{\rho}$$

Now, in metals, atoms are closely packed, and valence electrons are weakly attached to nuclei, allowing them to move freely within the material. These free electrons, or conduction electrons, move randomly without an external electric field but become directed under its influence. When an external electric field is applied, electrons exhibit a directed motion known as drift, acquiring a velocity referred to as drift velocity. This drift velocity is dependent on the strength of the electric field (E).

$$v_d \propto \mathrm{E}$$

$$\text{or, } v_d = \mu_e \mathrm{E}$$

where μ_e = constant = electron mobility

Electron mobility is defined as the average drift velocity of electrons per unit electric field.

$$\mu_e = \frac{v_d}{E}$$

The current density 'J' is defined as the current flowing per unit cross-sectional area.

$$\therefore J = \frac{I}{a} = \frac{V}{l} \cdot \frac{1}{\rho}$$

As,

$$\frac{V}{l} = E, the\ electric\ field\ and$$

$$\frac{1}{\rho} = \sigma, the\ conductivity,$$

$$\therefore J = \sigma E$$

Current density is also expressed as the rate of charge flow per unit cross-sectional area, measured as the amount of charge passing through a unit area in unit time.

To illustrate, consider a conductor with length L and unit cross-sectional area, across which a voltage V is applied, inducing current flow due to electron movement.

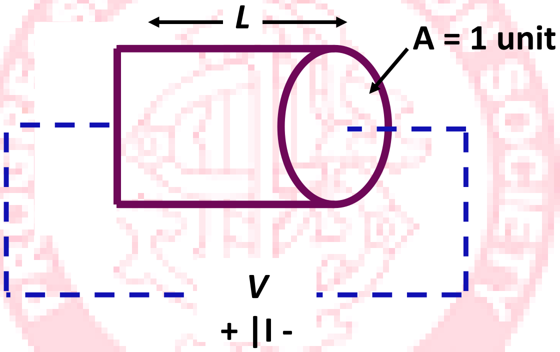

Figure 4.11. A conductor having a unit cross-sectional area and length L.

Let, n= number of electrons per unit volume

And, e= charge of an electron

Amount of charge that flows the unit area in 1s = J = nev_d

$$\therefore J = nevd$$

$$\therefore J = ne(\mu eE)$$

$$\therefore \sigma E = ne\mu eE$$

For the same electric field, the charges which acquire larger drift velocity are said to be more mobile.

$$\therefore \sigma = ne\mu_e$$

4.4.2 Conductivity in a Semiconductors:

In a semiconductor, the current is due to free electrons as well as holes.

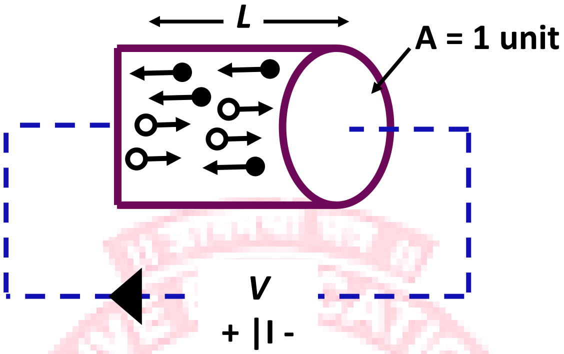

Figure 4.12. A semiconductor having a unit cross-sectional area and length L.

Since, $J = \frac{I}{a}$

$\therefore I = J \cdot a$

$\therefore I = neav_d$

$\therefore$ Current due to electrons:

$I_e = n_e eav_e$

Where,

$v_e = drift\ velocity\ of\ electrons$

$n_e = number\ density\ of\ electrons$

And, current due to holes:

$I_h = n_h eav_h$

Where,

$v_h = drift\ velocity\ of\ holes$

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$$n_h = number\ density\ of\ holes$$

The total current is:

$$I = I_e + I_h$$

$$\therefore\ I = n_e e a v_e + n_h e a v_h = ea(n_e v_e + n_h v_h)$$

$\therefore$ The current density, $J = \frac{I}{a} = e(n_e v_e + n_h v_h)$

Since, $J = \sigma E$

$$\therefore \sigma E = e(n_e v_e + n_h v_h)$$

$$\therefore \sigma = e(n_e \frac{v_e}{E} + n_h \frac{v_h}{E})$$

$$\therefore \frac{v_e}{E} = \mu_e, the\ mobility\ of\ electrons$$

And, $\frac{v_h}{E} = \mu_h, the\ mobility\ of\ holes$

$$\therefore \sigma = e(n_e \mu_e + n_h \mu_h)$$

a. ***For intrinsic semiconductor***, $n_e = n_h = n_i$, where n_i is called the density of intrinsic charge carriers.

$$\therefore \sigma = n_i e(\mu_e + \mu_h)$$

b. ***For n-type semiconductor***, $n_e \gg n_h$

$\therefore \sigma \approx n_e e\, \mu_e$, **where $n_e \approx n_d$ (n_d is the density of electrons at the donor level)**

As each donor atom contributes one free electron, n_e is also the density of donor impurity atoms.

c. ***For p-type semiconductor***, $n_h \gg n_e$

$\therefore \sigma \approx n_h e\, \mu_h$, **where $n_h \approx n_a$ (n_a is the density of electrons at the acceptor level)**

Where, n_h is the density of holes which is same as the density of acceptor impurity atoms.

In semiconductors, two types of currents exist:

- Drift Current: The flow of electrons and holes due to an externally applied electric field.
- Diffusion Current: The flow of charge carriers resulting from differences in their density.

Numericals: Example and Practice Problems: Conductivity of Conductors and Semiconductors

Worked-out Problem:

Example: Calculate the number of donor atoms that must be added to an intrinsic semiconductor to obtain the resistivity as 10^{-6} Ω cm. Given μe = 1000 $cm^2/V\text{-}s$. (Ans: 6.25 x 1021 per cm^3)

Sol. Given data:

$\rho = 10^{-6}\ \Omega\ cm$

$e = 1.6 \times 10^{-19}\ C$

$\mu_e = 1000\ cm^2/V\text{-}s$

Formula:

$\rho = 1/\sigma$

$= 1/n_e\, e\, \mu_e$

$\therefore n_e = 1/\ \rho\, e\, \mu_e$

$= 1/(10^{-6} \times 1.6 \times 10^{-19} \times 1000) = 6.25 \times 10^{21}$ per cm^3

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Problems:

4.3 Calculate the number of acceptors to be added to a Germanium sample to obtain the resistivity of 10 Ω cm. Given mu= 1700 $cm^2/V\text{-}s$. (Ans: 3.676 x 10^{14} per cm^3)

4.4. Calculate the conductivity of pure silicon at room temperature when the concentration of carriers is 1.5 x $10^{16}/(m^3)$ and the mobilities of electrons and holes are 0.12 and 0.05m^2/ V-s respectively at room temperature. (Ans: 4.08 x 10^{-4} S/m)

4.5. Calculate the resistivity for a germanium PN junction at room temperature. If both p and n regions are doped equally and to extent of one atom per 10^6 germanium atoms. Atomic weight = 72.6, Density =5.32 g/cm3, Mobility μ_e = 3800 cm^2/V-s. (Ans: 37.3 Ω-cm)

4.6. Find the drift velocity for an electron in silver wire of radius 1 mm and carrying a current of 2A. The density of wire is 10.5 gm/cc Avogadro's number = 6.023×10^{23}/gm mole. (Ans: 0.0067 cm/s or 67 µm/s)

4.7. Calculate the number of donor atoms that must be added to an intrinsic semiconductor to obtain a resistivity of 12 ohm-cm (mobility of electrons-500cm^2 /V-S).

4.5 Fermi Dirac Distribution Function

4.5.1 Fermi Level:

The Fermi level represents the highest occupied energy state at absolute zero temperature. It serves as a boundary between occupied and unoccupied energy levels. This concept facilitates understanding of energy level occupancy between the valence and conduction bands. However, it's not necessarily an actual electron energy level but rather a statistical concept to aid our understanding.

Fermi level in conductors:

In conductors, the Fermi level lies in the conduction band (within a band of allowed energy states), allowing for a high density of free electrons (. This means that even at room temperature, many electrons can easily move into higher energy states, contributing to electrical conductivity. The Fermi level is crucial in understanding the electrical properties and behavior of materials in various conditions. At this level, half of the quantum states are occupied in a solid.

Fermi level in semiconductors:

The location of the Fermi level is material-dependent. For ideal intrinsic semiconductors, it is centered within the bandgap. When doped with impurities (n-type or p-type), the Fermi level shifts:

- In n-type semiconductors, where extra electrons are provided, the Fermi level moves closer to the conduction band.
- In p-type semiconductors, where there are holes (missing electrons), the Fermi level shifts closer to the valence band.

This shift affects the electrical conductivity and the behavior of the semiconductor in devices.

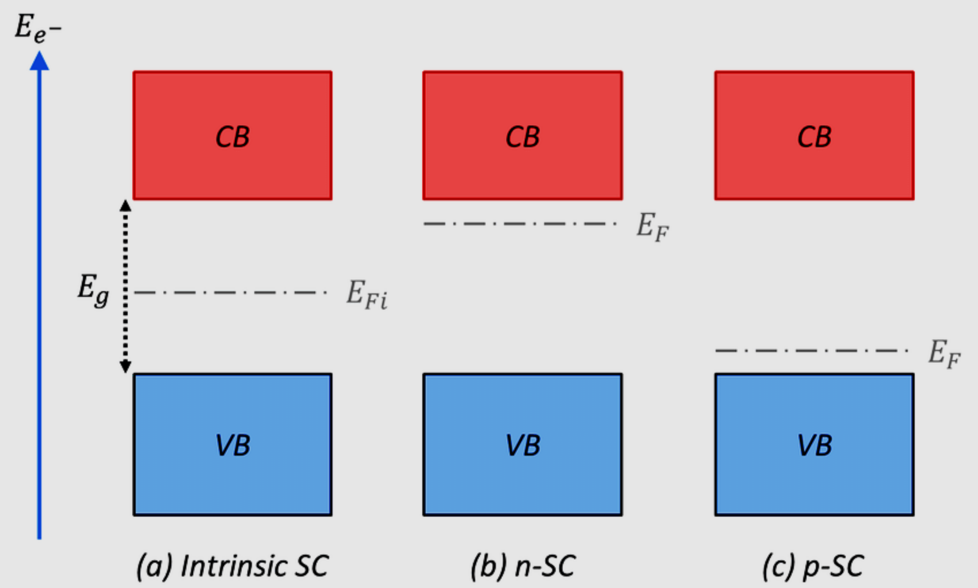

Figure 4.13. Illustrated scheme showing the Fermi level position within the band gap in the case of (a) intrinsic, (b) n-type and (c) p-type semiconductor.[3]

4.5.1 Fermi Dirac Distribution Function:

Different types of particles have varying probabilities of occupying available energy states. Statistically, there are three categories of particles:

1. **Identical particles:** These are indistinguishable from each other if their wave functions overlap, meaning they cannot be uniquely identified as separate particles even in principle. When they are spaced far apart and do not have overlapping wave functions, they can behave as distinguishable particles and follow the Maxwell-Boltzmann distribution, which is typical for classical particles, like gas molecules at higher temperatures or low densities.

2. **Identical particles with integer or zero spins**: These particles have overlapping wave functions. Because they are indistinguishable, they obey the Bose-Einstein distribution, hence known as bosons, Bosons can occupy the same quantum state simultaneously (e.g., photons in a laser).
3. **Identical particles with odd integer spins**: These particles with half-integer spins (with spins like 1/2, 3/2, 5/2, …) are fermions and obey the Pauli exclusion principle, meaning no two fermions can occupy the same quantum state simultaneously. They are indistinguishable in quantum mechanics and follow the Fermi-Dirac distribution, which applies to particles like electrons, protons, and neutrons.

Therefore, the distribution of electrons across energy levels at varying temperatures is governed by the Fermi-Dirac distribution function. This fundamental concept, developed by Fermi and Dirac in 1926, provides the probability of electron occupation at a given energy level E through the function P(E).

$$P(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

Where,

P(E) = probability of an electron occupying the energy state E

E_F = Fermi energy

k = Boltzmann constant

T = Absolute temperature

Probability of a Particle at T=0 K for E > E_f

$$\boldsymbol{P(E) = \frac{1}{1 + e^{(E-E_F)/kT}}}$$

If E > E_f, the exponent $(E-E_F)/kT \to +\infty$, so $e^{(E-E_F)/kT} \to \infty$

$$\mathrm{P(E)} = \frac{1}{1 + e^{\infty}} = \frac{1}{1 + \infty}$$

$\therefore \mathrm{P(E)} = 0$

Therefore, no electron can have energy greater than the Fermi energy at 0 K. Hence, all energy states above Fermi energy are empty at 0 K.

Probability of a Particle at T=0 K for E < E_f

$$\boldsymbol{P(E) = \frac{1}{1 + e^{(E-E_F)/kT}}}$$

If E < E_f , the exponent $(E-E_F)/kT$ approaches −∞, so $e^{(E-E_F)/kT} \rightarrow 0$

$$\mathrm{P(E)} = \frac{1}{1 + \mathrm{e}^{-\infty}} = \frac{1}{1 + 0}$$

$\therefore \mathrm{P(E)} = 1$

Therefore, all electrons occupy energy states below the Fermi energy at 0 K. Thus, all energy states below Fermi e nergy are filled and those above Fermi energy are empty at 0 K. Hence, Fermi energy is the highest occupied energy state at 0 K.

Probability of a Particle at T=0 K for E = E_f

$$\boldsymbol{P(E) = \frac{1}{1 + e^{(E-E_F)/kT}}}$$

If E = E_f ,

$$\mathrm{P(E)} = \frac{1}{1 + \mathrm{e}^{0}} = \frac{1}{1 + 1}$$

$\therefore \mathrm{P(E)} = \frac{1}{2}$

This shows that at T=0T = 0T=0 K:

- All states with energy $E<E_F$ are filled (since P(E)=1).
- All states with energy $E>E_F$ are empty (since P(E)=0).

Therefore, Fermi level represents energy state with a 50% chance of being occupied, assuming there is no forbidden gap. In semiconductors, the valence and conduction bands are separated

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by a forbidden gap. Thus, in semiconductors, the Fermi level can be defined as the energy level corresponding to 'centre of gravity' of valence band holes and conduction band electrons when 'weighted' according to their energies.

The fermi function for different temperature is shown in figure 4.14.

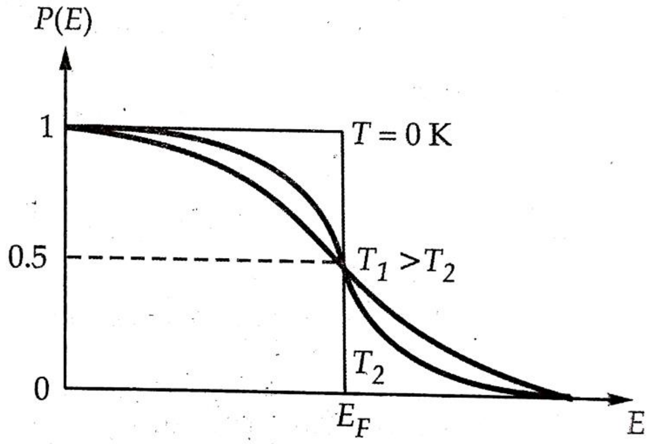

Figure 4.14. Fermi function for different temperatures.[4]

Position of Fermi Level in Intrinsic Semiconductors

The Fermi-Dirac probability function is:

$$\boldsymbol{P(E) = \frac{1}{1 + e^{(E-E_F)/kT}}}$$

and it gives the probability of an electron occupying a state of energy E.

The derivation of the position of Fermi level in intrinsic semiconductors is based on the following assumptions:

1. The widths of the valence and conduction bands are small when compared to the forbidden gap, E_g.
2. As band widths are small All levels in the band have same energy.
3. At 0 K, the solid is like an insulator.

At any other temperature (T),

Let, n_C = NP(E_C)

n_C = number of electrons in conduction band

$n_V =$ number of electrons in valence band

N = $n_C + n_V$ = number of electrons in both bands

P(E_C) = probability of an electron having an energy E_C in the conduction band

From probability theory,

$$P(E_C) = \frac{n_C}{N}$$

$$P(E) = \frac{1}{1 + e^{(E_C - E_F)/kT}}$$

$$\therefore n_C = \frac{N}{1+e^{(E_V - E_F)/kT}}$$

$$\text{Similarly, } n_V = \frac{N}{1+e^{(E_V - E_F)/kT}}$$

Since, N = $n_C + n_V$

$$N = \frac{N}{1+e^{(E_C - E_F)/kT}} + \frac{N}{1+e^{(E_V - E_F)/kT}}$$

$$\therefore e^{(E_C + E_V - 2\,E_F)/\mathrm{KT}} = 1$$

$$\therefore (E_C + E_V - 2\,E_F)/\mathrm{KT} = 0$$

$$\therefore (E_C + E_V - 2\,E_F) = 0$$

$$\therefore E_F = (E_C + E_V)/2$$

Therefore, Fermi level in intrinsic semiconductors is exactly in the middle of the forbidden gap (figure 4.15).

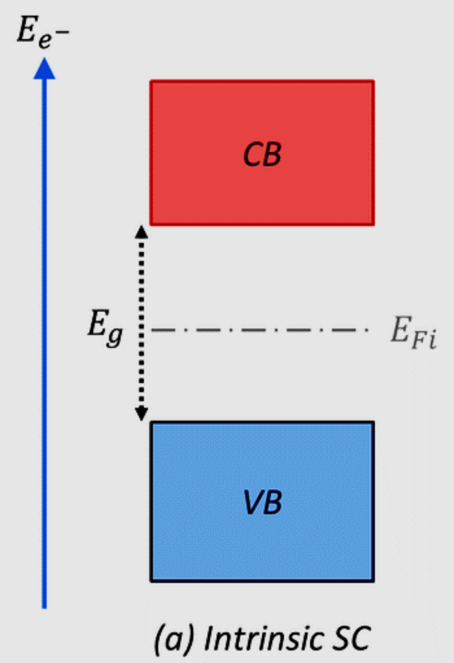

Figure 4.15. Position of Fermi level (E_{Fi}) in (energy band diagram of) intrinsic semiconductor.[3]

Position of Fermi Level in n-type Semiconductors

An n-type or pentavalent impurity semiconductor contains more conduction electrons than holes. This shifts the center of gravity upward, positioning the Fermi level above the midpoint of the forbidden band. Donor atoms introduce isolated energy levels that are situated close to the bottom of the conduction band, requiring minimal energy to excite an electron from the donor level into the conduction band, where it becomes available for electrical conduction (see figure 4.16).

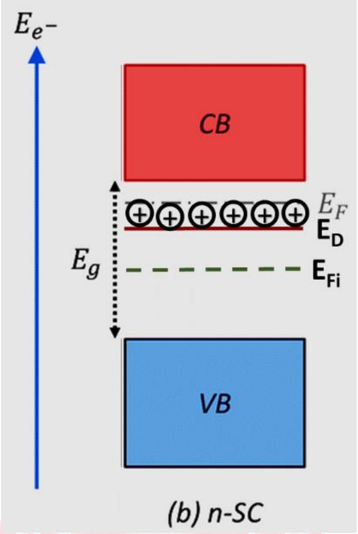

Figure 4.16. Position of Fermi level (E_F)in (energy band diagram of) n-type semiconductor at T= 0 K.[3]

In an extrinsic semiconductor, the position of Fermi level is influenced by two main factors: doping concentration and temperature**.**

Doping Concentration: When impurities (like donor atoms in an n-type semiconductor) are added, they introduce extra energy levels (donor levels) close to the conduction band. This shifts the Fermi level closer to the conduction band compared to a pure or intrinsic semiconductor, where the Fermi level would be near the middle of the energy gap.

Temperature Influence: At absolute zero (0 K), there's no thermal energy available to excite electrons into the conduction band. This means that all donor levels are filled with electrons, but no electrons have enough energy to jump into the conduction band. As a result, the probability P(E) of finding an electron up to the donor level is 1 (all donor levels are occupied), and above this level, in the conduction band, P(E)=0 (no electrons are in the conduction band).

Since the Fermi level represents an equilibrium point where the likelihood of an electron being present at that energy is 50%, it must lie somewhere between the highest donor level (E_D) and the bottom of the conduction band (E_C). Hence, at 0 K, the Fermi level E_F falls within the range $E_D \le E_F \le E_C$.

Position of Fermi Level in p-type Semiconductors

In a p-type semiconductor, the concentration of holes is higher than that of electrons. This shifts the center of gravity downward, positioning the Fermi level below the midpoint of the forbidden band. Acceptor atoms introduce isolated energy levels located near the top of the filled valence band. Only a small amount of energy is needed for an electron to leave the valence band and occupy an acceptor energy level, resulting in the creation of holes in the valence band.

At T=0 K, the Fermi level is located within the range $E_V \leq E_F \leq E_A$. At this temperature, the conduction band remains empty.

At T=0K, thermal energy is absent, meaning that no electrons have enough energy to move into the conduction band. In a p-type semiconductor, acceptor atoms have created energy levels (acceptor levels) near the top of the valence band, which are ready to accept electrons if energy is available.

Since there's no thermal excitation at T=0 K, electrons stay within the valence band, filling the lower energy states and leaving the conduction band entirely empty. The Fermi level E_F represents the energy level at which the probability of finding an electron is 50%. Given that the acceptor levels E_A are close to the top of the valence band E_V, and all states below E_A are likely occupied (figure 4.17), the Fermi level must lie somewhere between E_V (the top of the valence band) and E_A (the acceptor level).

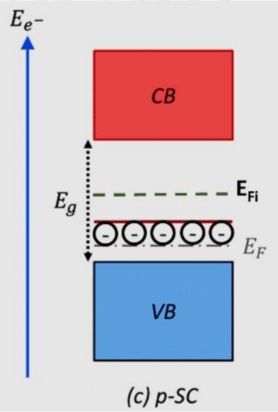

Figure 4.17. Position of Fermi level (E_F)in (energy band diagram of) p-type semiconductor at T= 0 K.[3]

This range, $E_V \leq E_F \leq E_A$, reflects the fact that, at absolute zero, electrons occupy the lowest energy states, and there are no conduction electrons, positioning the Fermi level within this defined range.

4.6 *p-n* Junction Diode

A junction diode is a type of semiconductor device that allows current to flow in only one direction. It is created by joining P-type and N-type semiconductor materials together, forming a junction with unique electrical properties. This junction creates a one-way path for current, which is the essential characteristic of a diode.

4.6.2 Structure of PN Junction Diode

- **P-type material**: This side is made by doping the semiconductor (typically silicon or germanium) with elements like boron, which have fewer valence electrons than silicon. This creates "holes" (positive charge carriers) in the material.
- **N-type material**: This side is doped with elements such as phosphorus, which have more valence electrons, creating free electrons (negative charge carriers).

When the P-type and N-type materials are joined, the electrons and holes near the junction combine, forming a region called the **depletion region**. This area is depleted of mobile charge carriers and thus acts as an insulator.

The energy barrier (Potential Barrier) is formed at the junction between the p-type and n-type semiconductor regions. This barrier prevents charge carriers (electrons and holes) from diffusing across the junction at equilibrium. When the p-type and n-type materials are joined, free electrons from the n-region (which has a higher concentration of electrons) diffuse into the p-region, and holes from the p-region diffuse into the n-region. As they move, they leave behind charged ions—positive ions in the n-region and negative ions in the p-region. This creates a region around the junction called the depletion region that is depleted of free charge carriers. The separation of charges in the depletion region generates an electric field. This field acts as a barrier, preventing further movement of electrons and holes across the junction. The electric field in the depletion region creates a barrier potential (also called the built-in potential), typically about 0.7V for silicon and 0.3V for germanium. This potential opposes the flow of additional electrons and holes, maintaining equilibrium.

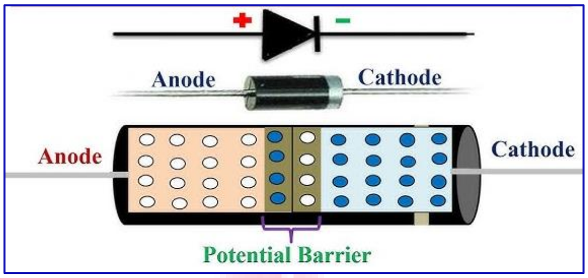

Figure 4.18. PN Junction Diode[5]

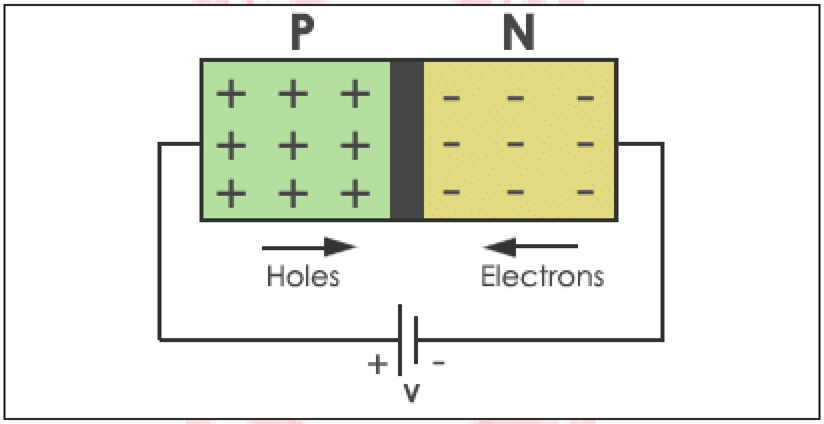

Figure 4.19. PN Junction Diode -Forward Biased[5]

Fermi Level in P-Type Semiconductor

In a P-type semiconductor, the Fermi level is closer to the valence band because the material has been doped with acceptor atoms (such as boron in silicon). These acceptor atoms create additional energy states just above the valence band, making it easier for electrons to leave the valence band and create holes. With more holes near the valence band, the Fermi level indicates that holes dominate electrical conduction in the P-type material.

Fermi Level in N-Type Semiconductor

In an N-type semiconductor, the Fermi level is closer to the conduction band because the material is doped with donor atoms (such as phosphorus in silicon). These donor atoms introduce additional energy states near the conduction band, making it easier for electrons to occupy the conduction band. With more free electrons near the conduction band, the Fermi level in N-type material reflects electron-dominated conduction.

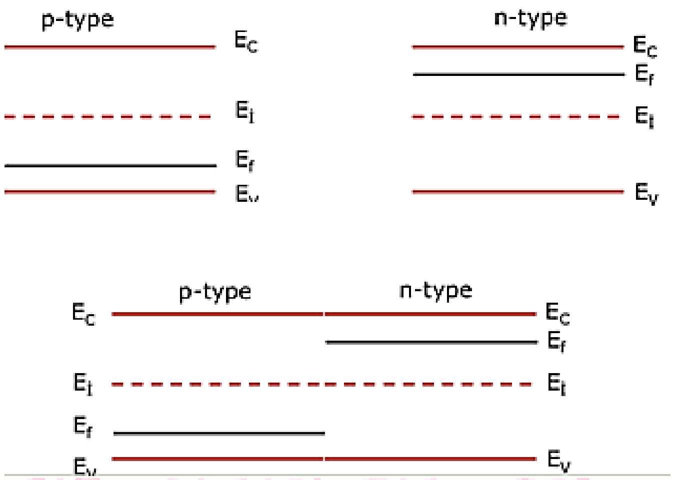

Figure 4.20. Energy diagram of a PN junction diode.[6]

Diffusion in Semiconductors

Diffusion is the process by which particles, such as electrons and holes, move from regions of high concentration to regions of low concentration. In a semiconductor, when P-type and N-type materials are brought together to form a PN junction, electrons from the N-type region (where electrons are the majority carriers) diffuse into the P-type region, and holes from the P-type region (where holes are the majority carriers) diffuse into the N-type region. This movement happens because particles naturally spread out to equalize concentrations across the material, i.e., diffusion causes the movement of electrons and holes across the junction, initiating charge separation. The diffusion process is crucial in forming the depletion region at the PN junction, as it leads to the initial charge redistribution.

Depletion Layer in a PN Junction

The depletion layer (or depletion region) is the area around the PN junction where mobile charge carriers (free electrons and holes) are depleted. As electrons and holes diffuse across the junction, they recombine and neutralize each other, creating a region near the junction that lacks

When electrons from the N-type region combine with holes in the P-type region, they leave behind positively charged donor ions in the N region and negatively charged acceptor ions in the P region. This buildup of fixed ions creates an electric field that opposes further diffusion of electrons and holes. The electric field in the depletion region acts as a barrier, preventing further movement of carriers across the junction. The width of the depletion region depends on factors such as the doping concentration in each region and the external voltage applied across the diode (forward or reverse bias). Under reverse bias, the depletion region widens, while under forward bias, it narrows.

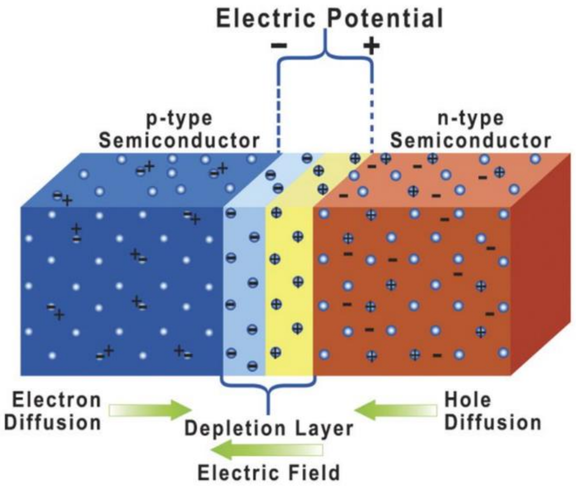

Figure 4.21. Processes involved in PN junction diode.[6]

4.6.2 Working of a PN Junction Diode

When the p-type and n-type materials are joined, they form a depletion region at the junction, with a built-in potential barrier that prevents charge carriers from crossing freely.

The working of the diode depends on the type of external bias applied:

(a) Zero Bias (Equilibrium Condtion):

In P-type semiconductors, the Fermi level is positioned near the valence band's top, whereas in N-type semiconductors, it's located near the conduction band's bottom. Due to this difference, the Fermi level on the P-side is lower than on the N-side, prompting electrons to flow across the boundary to the P-side, equalizing the Fermi levels. To accommodate this alignment, the band edges in both specimens shift, altering the energy band diagram. Initially (figure 4.22), the bands are separate, but after alignment (figure 4.23), the bands bend to facilitate the equalization of Fermi levels, resulting in a new energy band diagram.

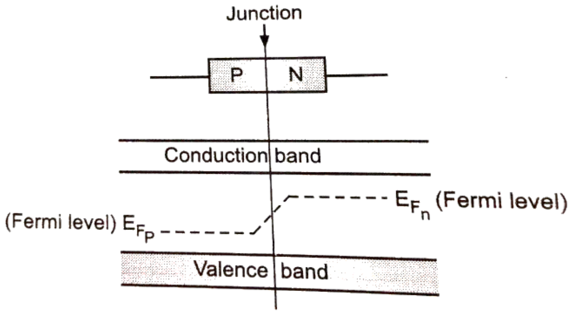

Figure 4.22. Non-equilibrium energy band picture of a p-n junction.[7]

At the junction, the P-type conduction band is elevated by the potential barrier (eV_B) relative to the N-type conduction band. This shift positions minority electrons in the P-type conduction band at a higher energy level than majority electrons in the N-type conduction band. Consequently, electrons moving from the P-region into the N-region do not encounter a potential barrier. In contrast, electrons crossing from the N-region into the P-region face a potential barrier (eV_B). This equilibrium band configuration for a zero-bias diode is illustrated in Fig. 4.23.

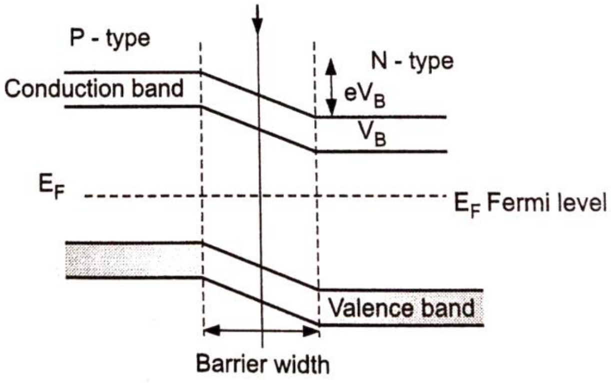

Figure 4.23. Shifting of the band in P and N-type semiconductors.[7]

(b) Forward Bias:

In forward bias, an external voltage is applied such that the p-type region is connected to the positive terminal and the n-type region to the negative terminal. This external voltage disrupts equilibrium, altering energy bands and shifts Fermi levels. The negative terminal's connection to the N-side increases the energy of N-side electrons by eV (where V is the applied voltage). Consequently:

- Fermi level rises by eV
- Energy bands adjust to accommodate this shift
- Potential barrier reduces to $e(V_B - V)$
- Barrier width decreases

As a result, electrons crossing the junction from the N-side encounter a lowered potential barrier, facilitating easy passage. For conduction to occur in a PN junction diode, the forward bias voltage must be greater than the barrier potential.

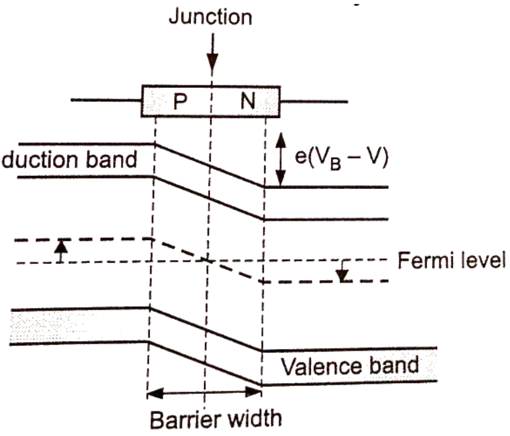

Figure 4.24. Forward bias.[7]

(c) Reverse Bias:

In reverse bias, the p-type region is connected to the negative terminal and the n-type region to the positive terminal of the external voltage source. This setup shifts the Fermi levels by lowering it on N-side by an amount eV in a way that widens the depletion region.

This configuration:

- Lowers the N-side Fermi level by eV.
- Increases the barrier height to $e(V_B + V)$.
- Widens the depletion layer (figure 4.25).

As a result:

- Majority electrons in the N-side face a higher potential barrier.
- Fewer electrons cross the junction from N-side to P-side.
- Current flow is significantly reduced.

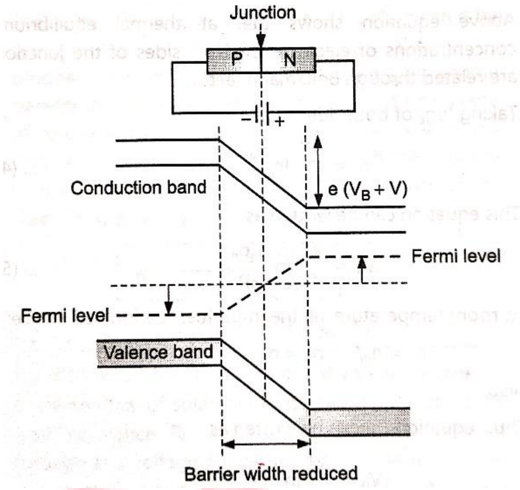

Figure 4.25. Reverse bias.[7]

Table 4.2. Summary of the bias conditions in a PN junction diode.

Bias Type	Depletion Region	Barrier Potential	Current Flow
Zero Bias	Present	Fixed	No net current
Forward Bias	Narrows	Decreases	High (conducting)
Reverse Bias	Widens	Increases	Very low (blocking)

4.7 Solar Cell

A photoelectric cell, also known as a photocell or photodetector, is a device that generates an electric current or voltage when exposed to light. This effect, known as the photoelectric effect, occurs when photons (light particles) strike a material, causing it to release electrons. The released electrons then create an electric current, or in some cases, change the electrical properties of the material.

There are three types of photoelectric cells:

1. Photo-emissive cell
2. Photo-voltaic cell
3. Photo-conductive cell

A solar cell, also known as a photovoltaic (PV) cell, is an electronic device that converts sunlight directly into electricity through the photovoltaic effect. Solar cells are the building blocks of solar panels, which generate clean and renewable energy by harnessing the sun's power.

4.7.1 Structure of a Solar Cell

A solar cell is structured in layers that work together to convert sunlight into electricity. The typical solar cell is made from silicon, a semiconductor material that efficiently converts light into electrical energy. The key layers and components in a standard silicon solar cell are explained below:

1. Antireflective Coating

The topmost layer of a solar cell is an antireflective coating that reduces reflection and helps more sunlight enter the cell. Without this coating, a significant portion of light would simply bounce off the surface of cell, reducing efficiency. Materials like titanium dioxide or silicon nitride are commonly used for this purpose.

2. Top Contact Grid (Front Electrode)

This is a metal grid pattern on the surface of the cell that allows electrons generated by sunlight to be collected and transferred to an external circuit. The grid design is chosen to strike a balance between maximizing light exposure to the silicon layer below and minimizing resistance for current flow. Silver is often used for this grid due to its high electrical conductivity.

3. N-Type Silicon Layer

Just below the antireflective coating and top contact grid is the n-type silicon layer. This layer is created by doping silicon with a small amount of phosphorus, giving it extra electrons (negative charge carriers). The n-type layer plays a crucial role in helping to form the electric field at the junction with the p-type layer.

4. P-Type Silicon Layer

Below the n-type layer lies the p-type silicon layer, which is doped with boron, providing it with "holes" (or positive charge carriers). This p-type layer works in conjunction with the n-type layer to create a PN junction—the critical part of a solar cell where the conversion of light to electricity takes place.

5. PN Junction (Depletion Region)

The interface where the n-type and p-type silicon layers meet is known as the PN junction.

At the junction, electrons from the n-type region fill holes in the p-type region, forming an electric field. This region, known as the depletion region, acts as a one-way gate that allows electrons to flow in only one direction. When sunlight hits the solar cell, the energy from photons frees electrons, creating electron-hole pairs. The electric field at the junction pushes the electrons towards the n-type layer and the holes toward the p-type layer, generating current.

6. Back Contact (Back Electrode)

The back contact is a layer of conductive metal (typically aluminum) placed at the bottom of the cell. It collects electrons that travel through the circuit and returns them to the p-type layer, completing the electrical circuit. The back contact serves as a mirror that reflects any remaining light back through the cell, increasing efficiency by giving the silicon layer another chance to absorb the photons.

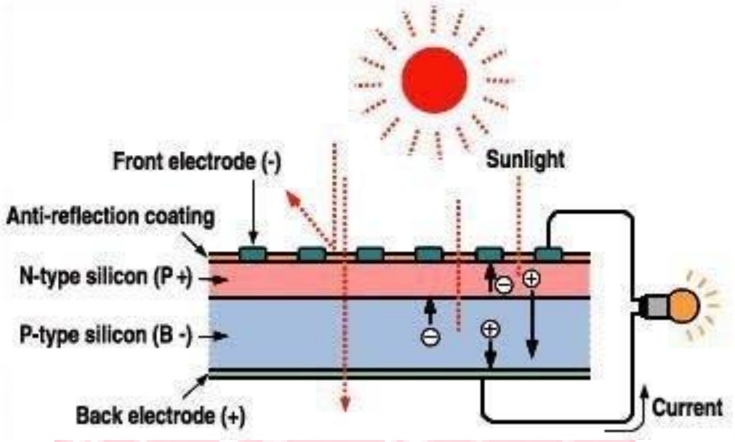

Figure 4.26. Structure of a solar cell.

Table 4.3. Summary of solar cell structure.

Layer	Function
Antireflective Coating	Minimizes reflection to maximize light absorption
Top Contact Grid	Collects and transfers electrons.
N-Type Silicon Layer	Supplies electrons (negative carriers).
P-Type Silicon Layer	Supplies holes (positive carriers).
PN Junction	Forms the electric field needed for current flow.
Back Contact	Collects electrons and completes the circuit.

4.7.2 Action/Working of a Solar Cell

The action of a solar cell is based on the photovoltaic effect, where sunlight is converted directly into electricity.

Sunlight Absorption: When sunlight hits the solar cell, photons (light particles) enter the cell. This energy ($h\nu$) is absorbed primarily in the semiconductor material (usually silicon), if $h\nu$ is greater than the band gap, E_g (figure 4.27).

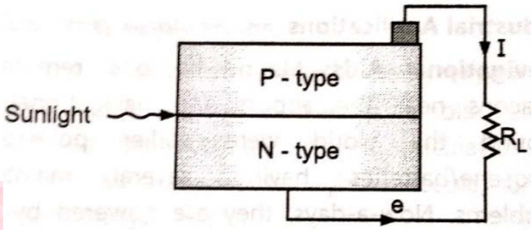

Figure 4.27. Solar cell p-n junction with load resistance R_L.[8]

Electron Excitation: Electrons-holes pairs are generated in both P-side and N-side of the junction. The energy from the photons excites electrons in the n-type and p-type layers. When photons have enough energy, they "knock" electrons loose from atoms in the silicon. This creates electron-hole pairs – electrons (negative charge) and holes (positive charge) that are now free to move.

Separation of Charge: Due to the electric field at the p-n junction (the boundary between n-type and p-type materials), free electrons are pushed toward the n-type side, while holes are pushed toward the p-type side. This separation of charges sets up a potential difference across the cell.

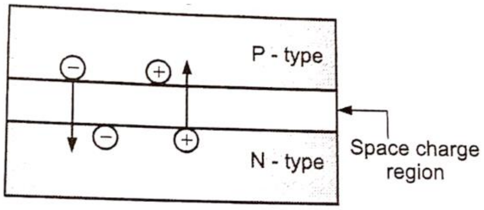

Figure 4.28. Diffusion of electrons and holes.[8]

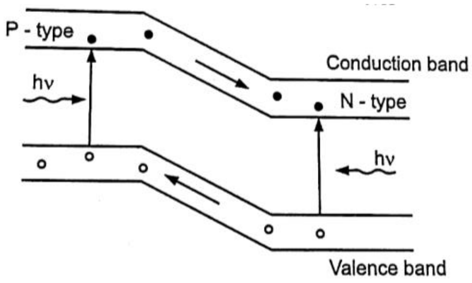

Figure 4.29. Energy nad diagram corresponding to diffusion of electrons and holes.[8]

Generation of Electric Current: The front and back metal contacts in the solar cell create a circuit. As electrons are pushed to the n-side and holes to the p-side, an electric field is established, and electrons begin to flow from the n-side through the external circuit back to the p-side, generating electric current. When a P-N junction is exposed to light and open-circuited, the separation of electrons and holes at the junction generates an open-circuit voltage (V_{oc}). Connecting a load resistance across the diode allows current to flow, exploiting the photovoltaic effect – the conversion of light into electrical energy. When the diode terminals are short-circuited, the resulting maximum current is referred to as the short-circuit current (I_{sc}).

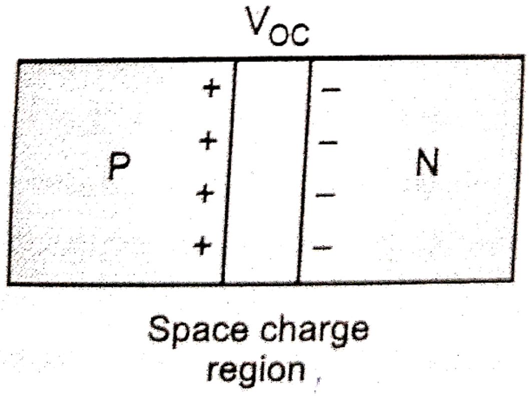

Figure 4.30. Space charge region.[8]

Output Power: The flow of electrons through the external circuit provides usable direct current (DC) power. This power can be used immediately, stored in batteries, or converted to alternating current (AC) through an inverter for general use.

Efficiency of Solar Cell:

Solar cells generate current as long as they receive sunlight.

- Current magnitude is directly proportional to light intensity.
- Generated electrical energy is in the form of DC voltage, approximately 0.5 V.
- Current varies with:
    - Surface area of the photovoltaic cell
    - Incident light intensity

The efficiency of a solar cell is defined as the ratio of the electrical power output to the solar power input (the amount of sunlight energy hitting the cell's surface), typically expressed as a percentage. It indicates how effectively the cell converts sunlight into usable electrical energy. The formula for calculating solar cell efficiency is:

Efficiency (η)= Power Output/Incident Solar Power

4.7.3 I-V Characteristics of a Solar Cell

The I-V (current-voltage) characteristics of a solar cell describe the relationship between the output current and the output voltage of the cell under illumination. It is studied by changing the load resistance R_L and measuring current flowing through and voltage appearing across it.

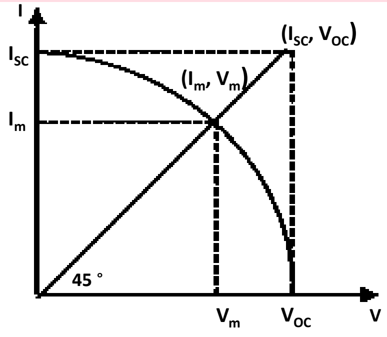

Figure 4.31. I-V characteristics of a solar cell.[9]

***Open-Circuit Voltage (V_{OC})*:** This is the maximum voltage across the solar cell when no current flows (open circuit), as the load increases at a particular stage when $R_L=\infty$. V_{OC} represents the maximum potential difference created by the cell. It's determined by the semiconductor properties and the amount of sunlight.

Short-Circuit Current (I_{SC}): This is the maximum current when the output terminals of the cell are shorted (zero voltage), and $R_L=0$. I_{SC} reflects the amount of current generated by light; it is proportional to the intensity of the sunlight and depends on the cell’s area and material quality.

Maximum Power Point (MPP): The point on the I-V curve where the product of current (I) and voltage (V) is maximum, giving the highest power output. The MPP represents the most efficient operating point of the solar cell. At this point, the cell delivers its maximum power (P_m). To get P_m from the solar cell I-V Curve, draw a line at 45° passing from origin, the point (V_m, I_m), where the line will cut the curve, will give P_m.

$$P_m = V_m \times I_m$$

I_m: maximum usable current

V_m: maximum usable voltage

Fill Factor (f): The fill factor is a measure of the "squareness" of the I-V curve. It is the ratio of maximum usable power (P_m) to ideal power, and is given by the ratio:

$$f = \text{Usable power}/\text{Ideal Power}$$

$$f = (V_m \times I_m)/(V_{OC} \times I_{SC})$$

$V_m \times I_m$: experimentally obtained maximum power of the solar cell

$V_{OC} \times I_{SC}$: theoretically obtained maximum power of the solar cell

A higher fill factor indicates a more efficient solar cell. It reflects the quality of the solar cell and its ability to convert energy. The shape of the IV curve indicates how efficiently the cell operates under different load conditions.

4.7.4 Applications of Solar Cell

Solar cells have become integral in many areas, offering sustainable energy solutions with diverse applications across industries, social sectors, and consumer markets.

1. Industry Applications

- Power Generation: Solar cells are widely used in large-scale solar farms to generate electricity, which is fed into the power grid. Countries worldwide are investing in solar power plants to support cleaner energy grids.
- Telecommunications: Remote telecommunications equipment, such as relay stations and towers, often rely on solar cells for uninterrupted power supply, particularly in locations without a stable electrical grid.
- Agriculture: Solar cells power water pumps, irrigation systems, and lighting in rural areas, allowing farmers to increase efficiency and crop yield. Greenhouses also use solar panels to control temperature and lighting.
- Transportation: Solar cells are integrated into electric vehicle charging stations and some vehicle designs, reducing reliance on fossil fuels and supporting the transition to greener transport options.

2. Social Applications

- Rural Electrification: Solar cells play a key role in bringing electricity to off-grid communities, providing reliable power for lighting, refrigeration, and communications in remote or developing areas. This helps improve living standards and supports education and healthcare services.
- Emergency Power Supply: During natural disasters, solar-powered mobile units provide essential electricity for emergency response, medical care, and communication, especially in areas where the regular power grid has been disrupted.

- Healthcare: In rural health clinics, solar cells power refrigeration units for vaccines, lighting for night-time operations, and medical equipment. This is crucial in areas with inconsistent electricity access.
- Education: Schools in off-grid areas benefit from solar cells for lighting, powering computers, and internet access, which enhances learning and access to resources.

3. Consumer Applications

- Residential Solar Panels: Homeowners use rooftop solar panels to generate electricity, reducing reliance on traditional power sources and lowering energy bills. With energy storage, households can maintain power even during grid outages.
- Portable Solar Chargers: Consumers use small, portable solar chargers for phones, tablets, and other devices, especially during travel, outdoor activities, or emergencies.
- Solar Gadgets: Solar-powered lights, fans, and even cooking devices are popular among consumers, providing an eco-friendly alternative to battery-operated or plugged-in devices.
- Wearables: Solar cells are now being integrated into wearable technology, such as solar-powered watches and backpacks, allowing users to charge devices on the go without access to electrical outlets.

4.8 Wide Band Gap Semiconductors

Wide band gap semiconductors are materials with a larger energy gap between the valence band and the conduction band compared to conventional semiconductors like silicon (Si) and gallium arsenide (GaAs). This wide band gap, typically greater than 2 electron volts (eV), gives them unique properties that make them highly valuable for certain applications.

Properties of a wide band gap semiconductor

Wide band gap semiconductors have unique properties that differentiate them from conventional narrow band gap materials like silicon (Si). These properties make them particularly useful in high-power, high-temperature, and high-frequency applications. Here are some key properties:

1. High Band Gap Energy

- Wide band gap semiconductors have band gaps typically greater than 2 eV, compared to 1.1 eV for silicon.
- Examples include:
    - Gallium Nitride (GaN): ~3.4 eV
    - Silicon Carbide (SiC): ~3.3 eV
    - Diamond: ~5.5 eV
- This large energy gap means electrons require more energy to move from the valence band to the conduction band, making the material more stable under high temperatures.

2. High Thermal Stability

- They can operate at high temperatures, as the probability of electrons thermally jumping across the band gap is low.
- This stability allows devices made from wide band gap materials to maintain performance without degradation in harsh environments, where traditional semiconductors would struggle.

3. High Breakdown Electric Field

- Wide band gap semiconductors can withstand high electric fields before the material undergoes electrical breakdown.
- This property allows them to handle high-power applications, as they can support larger voltages without failure.
- For example:
    - SiC has a breakdown field approximately 10 times higher than silicon.
    - GaN also has a much higher breakdown field compared to silicon.

4. High Saturation Electron Velocity

- Wide band gap materials typically have high electron saturation velocities, meaning that electrons can move faster within the material under high electric fields.
- This makes them suitable for high-frequency and high-speed applications, such as radio frequency (R_F) and microwave devices.

5. Low Intrinsic Carrier Concentration

- Due to the large band gap, fewer electrons are thermally excited to the conduction band at room temperature.
- This results in lower intrinsic carrier concentrations, making wide band gap semiconductors less sensitive to temperature-induced conductivity.
- Consequently, devices made from these materials experience lower leakage currents, especially beneficial for high-temperature and low-noise applications.

6. High Thermal Conductivity

- Many wide band gap semiconductors, like SiC and diamond, have high thermal conductivity, which allows efficient heat dissipation.
- This property is critical for high-power applications, as it prevents overheating and improves device longevity.

7. Radiation Hardness

- Wide band gap semiconductors are more resistant to radiation damage compared to traditional materials, which makes them suitable for aerospace, military, and nuclear applications.
- The radiation tolerance ensures stable operation even in environments with high levels of radiation, where other materials might degrade quickly.

8. Efficient Light Emission

- Wide band gap semiconductors can emit light in the visible or ultraviolet (UV) spectrum, making them ideal for optoelectronic applications like LEDs and laser diodes.

- Materials like GaN are used in blue and UV LEDs, while other wide band gap materials are used in various display and lighting technologies.

Examples of Wide Band Gap Semiconductors

1. Silicon Carbide (SiC): SiC has a band gap of about 3.3 eV and is highly suitable for power electronics, such as power inverters and switches in electric vehicles and renewable energy systems.
2. Gallium Nitride (GaN): GaN has a band gap of about 3.4 eV and is widely used in high-frequency, high-voltage, and optoelectronic devices, including RF amplifiers, power transistors, and LEDs.
3. Diamond: With a band gap of about 5.5 eV, diamond is an extreme wide band gap semiconductor that can handle high power and temperature conditions. It is still under research for practical electronic applications but holds potential for future high-power, high-temperature devices.

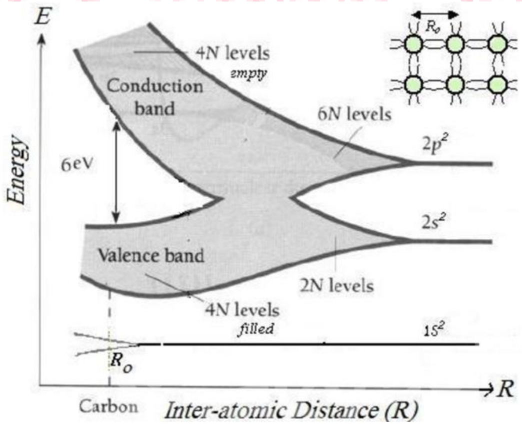

Figure 4.32. Energy band diagram of diamond.[10]

Applications of Wide Band Gap Semiconductors

1. Power Electronics: Wide band gap semiconductors are used in power converters, inverters, and switches that need to handle high voltages and currents efficiently, especially in electric vehicles, renewable energy systems, and power grids.

2. High-Frequency Electronics: GaN-based devices are extensively used in microwave and RF applications due to their ability to operate at high frequencies with reduced losses.
3. Lighting and Display Technologies: GaN and similar materials have transformed lighting technology, enabling energy-efficient LED lighting and displays with a broad color range.
4. Harsh Environment Applications: Wide band gap semiconductors can operate reliably in environments with high radiation, extreme temperatures, and high power, making them suitable for aerospace and military applications.

Questions:

1. Describe the formation of energy bands in solids.
2. Explain valence, conduction bands, and the forbidden energy gap.
3. Give energy band pictures of lithium, beryllium, silicon, and diamond.
4. Derive an expression for conductivity in a metal.
5. Derive an expression for conductivity in intrinsic and extrinsic semiconductors.
6. What is Fermi Energy? Show the location of Fermi energy levels in intrinsic and extrinsic semiconductors at T=0 K and T> 0 K.
7. What is the Fermi function? Show that the fermi level lies at the center of the energy gap in an intrinsic semiconductor.
8. Explain the Fermi-Dirac distribution function specifying the meaning of each term.
9. Explain why a potential difference develops across an open-circuit PN junction.
10. Give an energy band picture of a PN junction diode and explain the effect of biasing on the band picture.
11. 'P-N junction is a unidirectional device'. Explain.
12. Explain the working of a P-N junction diode under forward and reverse bias conditions.
13. Explain the process that takes place in and around the depletion layer.
14. Write a note on the construction and characteristics of a solar cell.
15. Explain the working of a solar cell. Give the significance of the cell parameters, I_{SC}, V_{OC}, and fill factor.

Critical Thinking Questions

1. Why are intrinsic semiconductors typically poor conductors of electricity? How does temperature influence their conductivity, and why?
2. Consider a semiconductor device that operates at different temperatures. How might temperature changes affect the intrinsic carrier concentration and device performance?
3. How does doping modify the properties of a semiconductor? Could there be a scenario where excessive doping negatively impacts a device's performance?
4. In a p-n junction, why does the formation of the depletion region limit the flow of charge carriers? What factors determine the width of this region?
5. Describe a practical application where both n-type and p-type semiconductors are required. Why are both types necessary for the device's operation?
6. How would you explain the role of minority carriers in a semiconductor? How do they influence the behavior of a p-n junction under reverse and forward bias?
7. If you could only adjust the electron mobility or the carrier concentration to improve conductivity, which would you choose? Explain your reasoning.
8. Why are materials with high electron mobility preferred for high-speed electronics? How does mobility affect switching speeds and power dissipation?
9. In a solar cell, how does the p-n junction generate electricity from sunlight? What factors determine the efficiency of this conversion?
10. What are the potential impacts of semiconductor miniaturization on the reliability and performance of electronic devices? Are there any physical limits to miniaturization?

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