

CHAPTER ONE

**FUNDAMENTALS OF
SOLAR CELLS**

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FUNDAMENTALS OF SOLAR CELLS

Solar cells are basic building blocks for the fabrication of photovoltaic modules which are the main component in the solar photovoltaic power generation systems. A clear understanding of the science of the solar cells, the fabrication, the principle of operation, the electrical behavior and the efficiency, are essential to go into the technology aspects of solar photovoltaics. These aspects are discussed in detail in this chapter.

1.1 PHYSICS OF SEMICONDUCTORS

A solid can be a piece of copper or glass or wood; but distinct differences exist among the three due to the arrangement of atoms, the basic constituents in a solid.

In copper, there is a regular pattern of arrangement of atoms, which can be confirmed using x-radiation. Such a solid is called 'crystalline solid', wherein there is a long- range order of arrangement of atoms. In glass and wood, the situation is different.

The atoms in a crystal are held in position by 'bonds'. There are five idealized types of bonding: ionic, covalent, metallic, hydrogen and molecular, and each crystal is characterized by one of these types of inter atomic bonding. However,

in some cases, many bonds are formed by two or more of these idealized forms. Of these, the metallic and covalent bonds are relevant for us.

Solids with metallic bonding are excellent electrical conductors because of 'free' electrons (the outermost electrons in the atoms). Metals are mechanically tough and ductile. The solids with covalent bond are generally insulators electrically. They are extremely hard and have high melting points. The elements in the IV Group of the Periodic Table are characterized by covalent bonding.

Between these two categories of good conductors and insulators, there is an important group of solids called 'semiconductors'. These do not have 'free' electrons' to exhibit electrical conduction at low temperatures; but at room temperature, they show a modest electrical conductivity, which increases with temperature increase.

There are many semiconductor crystals, but silicon and germanium belonging to IV group of the periodic table are very important ones. The third group elements and fifth group elements chemically combine to form compounds which are semiconductors. Examples are GaAs, InAs, GaP, InP, InSb and so on. Similarly, group II elements combine with group VI elements forming compounds such as CdS, ZnS, CdTe which are semiconductors.

The electrical conductivity of semiconductor materials generally range from 1/10000 to 10000 mho/cm, which is far less than that of metals. The conductivity behavior of semiconductors may be explained with a simple model. The two-dimensional lattice structure of a typical semiconductor, silicon is shown in Fig.1.1(a). Each silicon atom has four nearest neighbours. It has 14 electrons in its atomic structure and four of them are in the outermost orbit which are weakly-bound to the nucleus. These four electrons are called 'valence electrons' which form 'covalent bonding' with the four nearest-neighbor atoms .ie, each valence electron of a silicon atom is shared by one of its four nearest neighbors.

The valence electrons thus help to bind one atom to the nearest neighbour resulting in these electrons being tightly bound to the nucleus. In a 'chemically pure' or 'intrinsic' silicon which contains no foreign atoms, this ideal situation exists at 0 deg.kelvin, and the crystal behaves as an electrical insulator since no free electrons are available. When the temperature of the crystal is raised or light is allowed to incident on it, the 'bond' gets broken and the valence electron becomes a free electron leaving behind a 'hole' as shown in Fig.1.1(b).

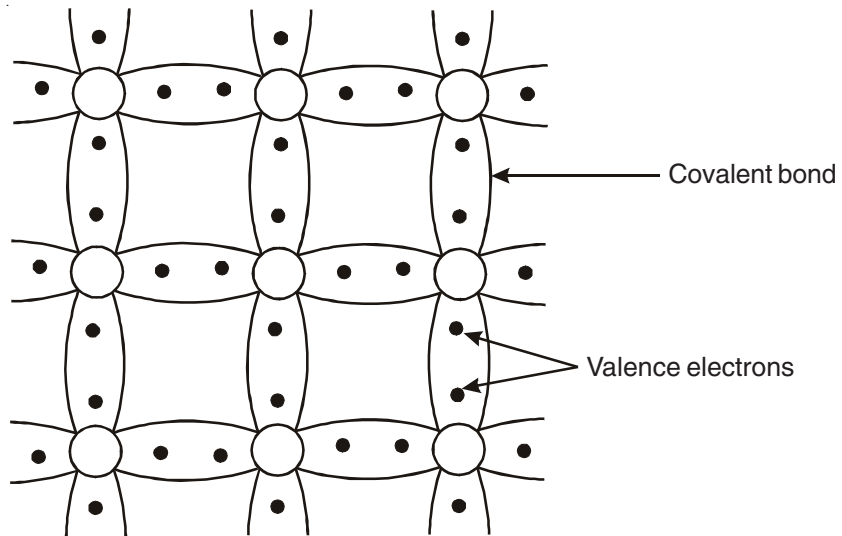


Fig. 1.1(a) Two-dimensional Silicon Lattice

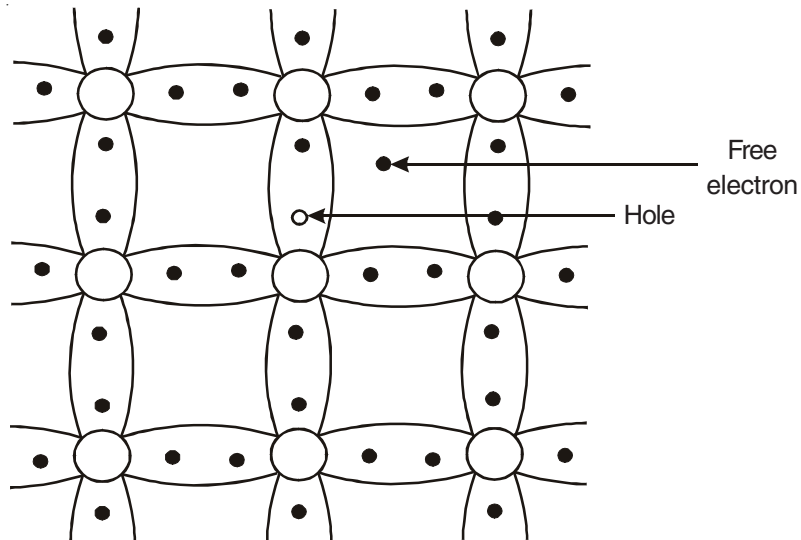


Fig. 1.1(b) Silicon Lattice with a broken covalent bond

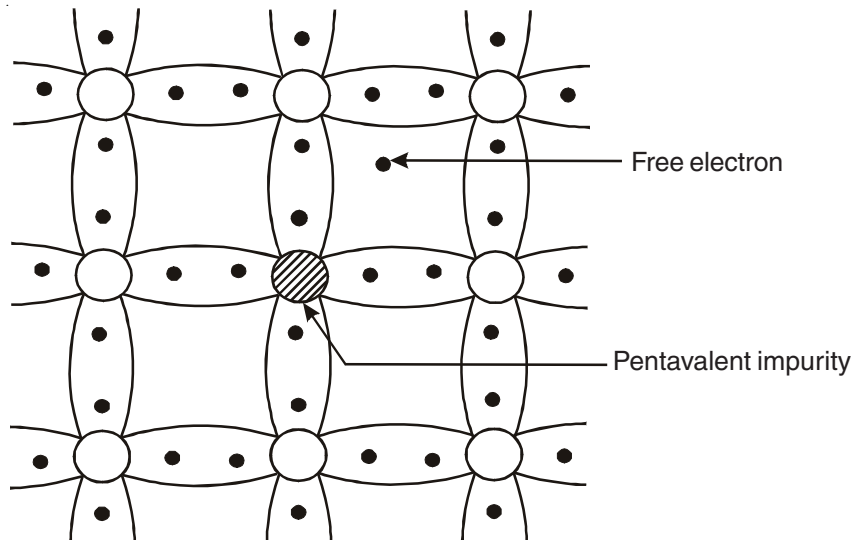


Fig. 1.1(c) Silicon Lattice with one Si atom displaced by a pentavalent atom

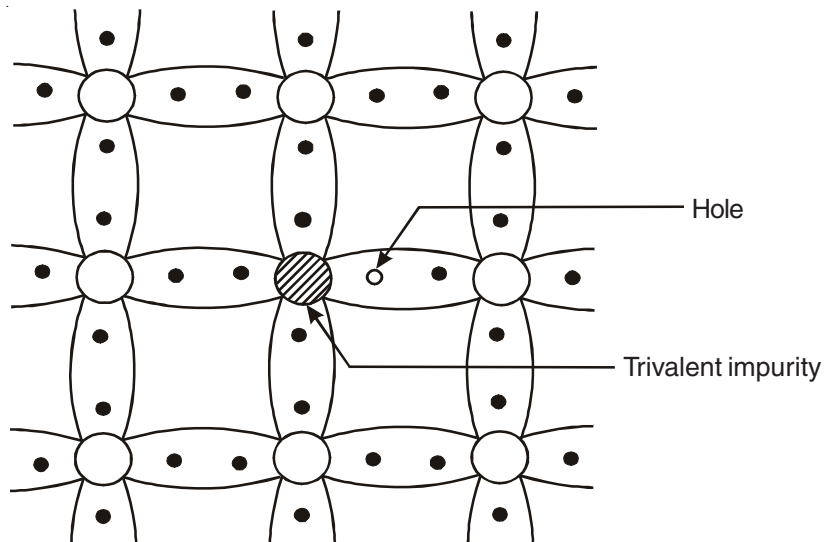


Fig. 1.1(d) Silicon Lattice with one Si atom displaced by a trivalent atom

The hole is an incomplete covalent bond. It takes energy equal to ‘band energy’ E_g , a characteristic parameter of a semiconductor, to separate an electron from the bonding and make it a ‘free’ electron, also referred to as ‘conduction’ electron.

For silicon, E_g is equal to 1.1 eV at room temperature. When a hole exists in a bond, it is relatively easy for a valence electron in a neighbouring atom to leave its covalent bond to fill the hole, leaving a hole in its original position. The ‘hole’ therefore effectively moves opposite to that of electron. The movement of holes, behaving like positive charges, constitute an electric current.

Consider a situation where a silicon atom is replaced by a pentavalent atom like phosphorous (P) as in Fig.1.1(c). P atom has five valence electrons and four of them occupy the covalent bonding and the fifth one nominally held in the bond can move freely as a carrier of current due to thermal excitation. The energy required to detach this electron is about 0.05 eV for silicon, which is very small compared to E_g . By adding pentavalent atoms, the creation of ‘extra’ free electrons are achieved, the density of these electrons depending on the dopant concentration. This type of doping is called n-type doping and the dopant is called ‘donor’ type.

On the contrary, a silicon atom is replaced by a trivalent atom like boron (B) which has three valence electrons as shown in Fig.1.1(d). Then bonding with only three nearest neighbors is complete. This atom can capture an electron from a nearby bond, establishing the fourth bond. The captured electron is not available for conduction, but a hole created in the original position of the electron conducts. This is called p-type doping wherein creation of extra holes are achieved, the hole density depending on the dopant concentration. This type of dopant is called ‘acceptor’ type.

Small amounts of dopants, few parts per million, introduced into the semiconductor structure can significantly increase the number of electrons available for breaking away from their atoms.

The valence electrons are confined to the valence band; but when light energy equal to or greater than E_g is incident, they move into the conduction band, creating an equal number of ‘holes’ in the valence band. In Fig.1.2, E_c represents the lowest energy that conduction electrons may have and E_v represents the lowest energy that ‘holes’ may have. E_g is the separation of conduction band edge from valence band edge.

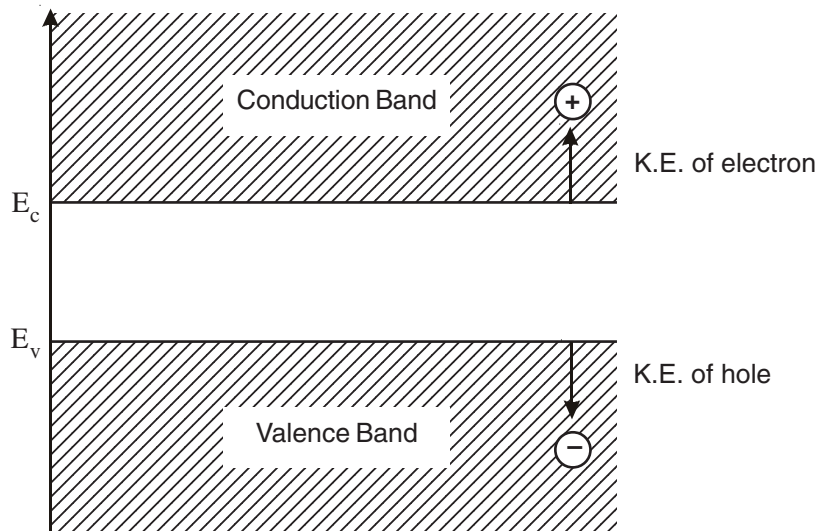


Fig. 1.2 Energy Band diagram of a Semiconductor, $E_c - E_v = E_g$

The electron density, 'n', and the hole density, 'p' are related to the band gap energy, E_g as

$$np = B e^{\left(\frac{E_g}{kT}\right)} = n_i^2 \quad \text{..... (1)}$$

where B is a constant, k is the Boltzmann constant and T is the temperature.

In a pure or intrinsic semiconductor, n and p are equal and represented by n_i , the intrinsic carrier concentration. In silicon, n_i is about 10^{10}cm^{-3} at room temperature.

The electrical conductivity may be altered by doping with small amounts of 'dopants' such as Group V (donor) or Group III (acceptor) elements of the periodic table. Each donor atom introduced into silicon crystal contributes one extra electron and if the donor density N_d is higher than n_i , then 'n' is approximately equal to N_d ; and from Equation (1),

$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_d} \quad \text{..... (2)}$$

In the donor-doped semiconductors called n-type semiconductors, $n \gg p$; i.e., electrons are majority charge carriers and holes are minority charge carriers.

For example, a silicon crystal doped with 10^{15}cm^{-3} atoms of fifth group element would have 'n' equal to 10^{15}cm^{-3} and 'p' equal to 10^5cm^{-3} .

If a third group element is added to silicon, each dopant atom creates one 'hole' and the semiconductor is referred as p-type semiconductor. If N_a is the acceptor density, then

$$p = N_a$$

and

$$n = \frac{n_i^2}{N_a} \quad \text{..... (3)}$$

In p-type, $p \gg n$; i.e., holes are majority charge carriers and electrons are minority charge carriers. The electrical conductivity of a doped semiconductor is represented as,

$$\sigma = q\mu_n n + q\mu_p p \quad \text{..... (4)}$$

where μ_n and μ_p are the 'electron' and 'hole' mobilities and q is the charge on the carrier. The mobilities of the charge carriers are characteristic of the semiconducting material and are dependent on doping concentration and the temperature of the material.

The nature of semiconductor can be changed by adding 'donors' to a p-type semiconductor and 'acceptor' atoms to an n-type semiconductor. If donor and acceptor concentrations become equal, the semiconductor remains 'intrinsic' because there would be no 'free' charge carriers.

1.2 GENERATION OF CHARGE CARRIERS DUE TO PHOTON ABSORPTION

If a semiconductor of band gap energy, E_g absorbs light energy, $h\nu$, greater than E_g , each absorbed photon raises one electron from valence band to

conduction band, creating one electron and one hole. Here ‘h’ is Planck’s constant and ν is the frequency of the light wave. The carrier generation rate per unit area of the semiconducting surface is therefore a function of E_g ; however, the reflection of incident light at the surface and incomplete collection of charge carriers affect the generation rate. Fig.1.3, indicates that low band gap semiconductors generate more electric current.

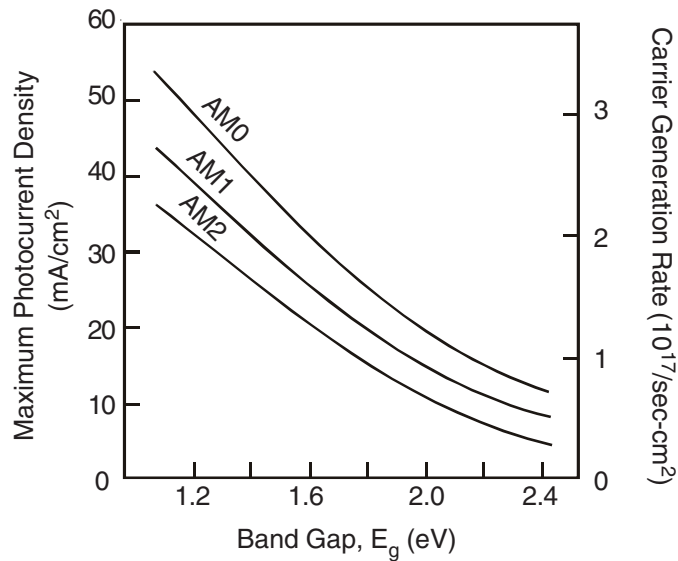


Fig. 1.3 Band Gap of the semiconductor Vs Maximum Photocurrent Density and Carrier Generation Rate

Actually, the incident light photons move a distance ‘x’ from the surface of the semiconductor before being absorbed. The decrease of photon flux from the surface is exponential in nature and the ‘flux’ at a distance ‘x’ is

$$P(x) = P(o) e^{-\alpha x} \quad \dots\dots\dots (5)$$

where α is the ‘absorption coefficient’.

The rate of generation of carriers per unit volume is

$$G(x) = -\frac{dP(x)}{dx} = \alpha P(o)e^{-\alpha x} \quad \dots\dots\dots (6)$$

The absorption coefficient is a function of photon energy, $h\nu$ and is zero for $h\nu < E_g$. In some semiconductors, α goes to zero abruptly and in others it occurs gradually. The abrupt change is a characteristic of ‘direct-gap’ semiconductors whereas a gradual change is a characteristic of ‘indirect-gap’ semiconductors. This behavior is an important consideration for choosing a semiconductor for solar cell fabrication.

Fig.1.4 illustrates the photon absorption rate and maximum cell current as a function of material thickness, for a direct-gap and an indirect-gap semiconductors. It is clear that for silicon, until the thickness is around 100 micrometers and above, all the light photons are not absorbed; whereas in GaAs, a thickness of 1 micrometer is sufficient to absorb all the photons. Evidently, direct-gap semiconductors are the most favored for the fabrication of solar cells due to large saving of the material.

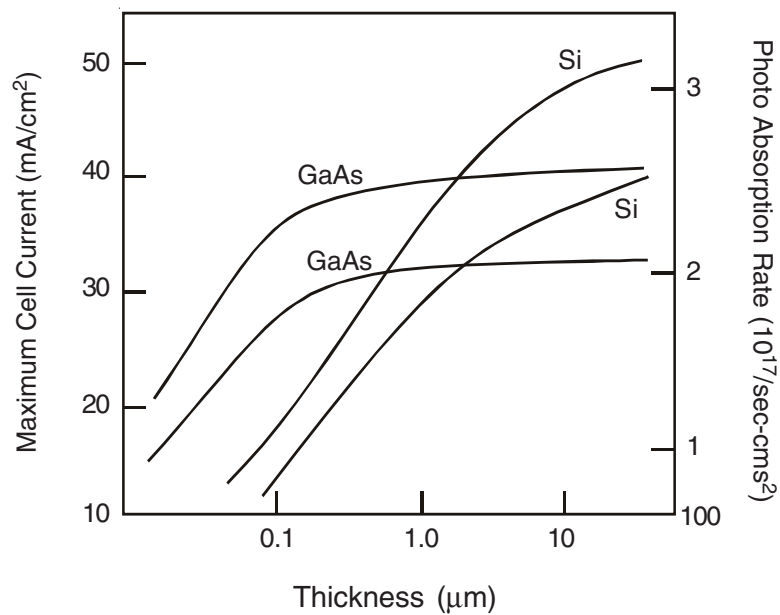


Fig. 1.4 Thickness Vs Photo Absorption Rate & Maximum Cell Current

If the carrier concentrations exceed their equilibrium values, the excess carriers ‘recombine’ and carrier annihilation occurs. The rate of annihilation is

$$\frac{n - n_0}{\tau} = \frac{p - p_0}{\tau} \text{ cm}^{-3}\text{sec}^{-1} \quad \dots\dots\dots (7)$$

where n_0 and p_0 are ‘equilibrium’ electron and hole densities respectively and τ is the recombination lifetime of the carriers. If τ is high in a semiconductor, it makes a very good solar cell material. In a near-perfect silicon, the recombination lifetime is around a few milliseconds, but in low quality silicon, the lifetime is very low due to the presence of electrically-active point defects, dislocations and even grain boundaries which hasten the recombination process.

Three types of recombination mechanisms operate depending on the nature of semiconductor and the doping density:

- (a) *band-to-band recombination, more dominant in direct-gap semiconductors of high doping densities,*
- (b) *Auger recombination, dominant in heavily-doped semiconductors,*
- (c) *recombination through traps dominant in highly-doped indirect-gap semiconductors.*

These three mechanisms of recombination are schematically shown in Fig.1.5. Generally, only one of these mechanisms predominates over the other two in a semiconductor; however, the total recombination rate is taken as sum of the recombination rates of the three mechanisms.

$$\frac{1}{\tau} = \left(\frac{1}{\tau_b} \right) + \left(\frac{1}{\tau_A} \right) + \left(\frac{1}{\tau_{tr}} \right) \quad \dots\dots\dots (8)$$

where τ_b , τ_A , τ_{tr} are the recombination rates due to the three mechanisms respectively. The recombination rate, τ is related to ‘diffusion length’, L , the distance travelled before the carriers recombine.

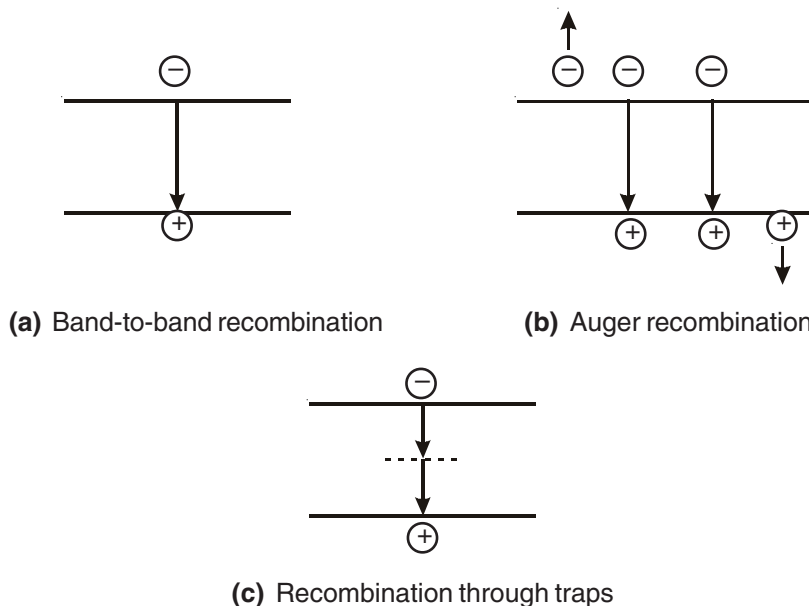


Fig. 1.5 Recombination Mechanisms

The excess carrier density of the minority carriers decreases exponentially with distance from the plane of the semiconductor where they are generated. The diffusion length, L is

$$L = \left[\frac{kT\mu\tau}{q} \right]^{\frac{1}{2}} \quad \text{or} \quad [D\tau]^{\frac{1}{2}} \quad \dots\dots\dots (9)$$

in terms of 'diffusion coefficient', D equal to $\left[\frac{kT\mu}{q} \right]$

1.3 THEORY OF p-n JUNCTION

Let us examine the operation of a p-n junction. The interface between a p-type region and n-type region of a semiconductor is called a p-n junction. This junction can be created in several ways in a semiconductor. The usual practice is to dope a slice of crystalline semiconductor with donors on one side and acceptors on the other. In Fig. 1.6(a), donor ions are represented by plus signs and electrons they donate by small filled circles. The acceptor ions are

represented by minus signs and the holes that are generated by small unfilled circles. Due to higher concentration of electrons on n-side and holes on p-side, the electrons tend to move from n- to p-side and the holes from p- to n-side. The holes which neutralised the acceptor ions near the junction in the p-region have disappeared due to combination with electrons which have diffused across the junction. Similarly, electrons in n-region have combined with holes that crossed the junction from p-region. The unneutralised ions in the neighborhood of the junction result in a charge density. Since this region is depleted by moving charges, it is called 'depletion region' or 'space charge region'. The width 'w' of this region is of the order of a few tenths of a micrometer.

The charge carriers exist only outside this region: to the right, they are predominantly 'holes' and to the left, they are 'electrons'. An electric field and a contact potential difference are created from a non-uniform charge concentration. This contact potential difference constitutes a potential energy barrier given by (Ref. 1), as shown in Fig. 1.6(b).

$$qV_d = kT \ln \left[\frac{N_d N_a}{n_i^2} \right] \dots\dots\dots (10)$$

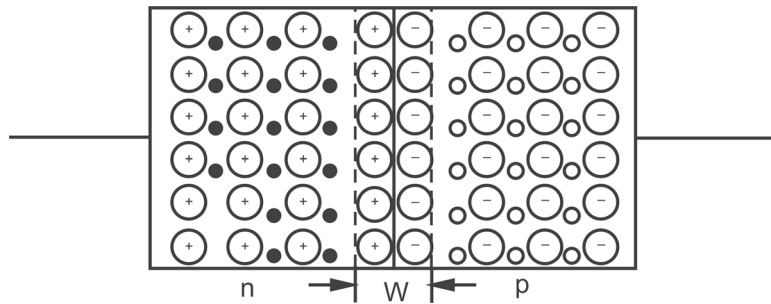


Fig. 1.6 (a) p-n junction

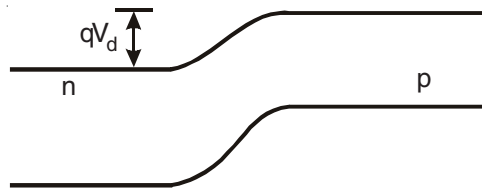


Fig. 1.6 (b) Band Diagram with no bias

When a voltage, V is applied across the p-n junction with p-side positive, then the junction is forward-biased and the energy diagram will be as shown in Fig.1.6(c). Here, the external field due to voltage V , opposes the field set up by the contact layer. Consequently, electrons freely move towards p-side and the holes towards n-side, because the potential barrier height is decreased resulting in a net current in the external circuit.

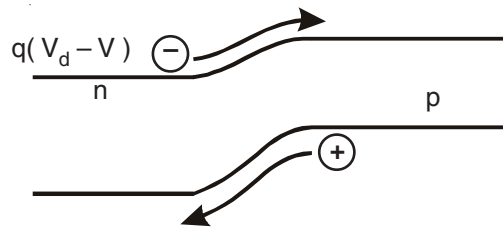


Fig. 1.6 (c) Band Diagram with forward bias, V

The electric currents resulting due to the motion of charge carriers may be expressed as

$$\frac{dI_n}{dx} - \frac{n_p - n_{p_0}}{q\tau_n} = 0$$

$$I_n = q\mu_n n_p E + qD_n \frac{dn_p}{dx} \quad \text{for electrons on p-side} \quad \dots\dots\dots (11)$$

and $\frac{dI_p}{dx} - \frac{p_n - p_{n_0}}{q\tau_p} = 0$

$$I_p = q\mu_p p_n E - qD_p \frac{dp_n}{dx} \quad \text{for holes on n-side} \quad \dots\dots\dots (12)$$

Here, I is the current density, D is the diffusion coefficient, and n_p and p_n are respectively the electron concentration on the p-side and hole concentration

on the n-side. Assuming that the doping levels on the two sides to be uniform, the equations can be solved for the injected current density, I_{inj} , using boundary conditions.

$$I_{inj} = I_o \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad \text{..... (13)}$$

where I_o is known as ‘reverse saturation current’ of the p-n junction. The current represented by this equation is the dominant one in high quality silicon p-n junctions. But in low quality junctions and in junctions made of high energy gap semiconductors, the ‘depletion region-recombination current’ which results from the recombination in the depletion region becomes significant.

At high current levels, I_{inj} follow an exponential relationship. The current-voltage (I-V) curves over a current range may be represented by

$$I = I_o \left[\exp\left(\frac{qV}{\gamma kT}\right) - 1 \right] \quad \text{..... (14)}$$

where I_o and γ are determined by curve fitting and their magnitudes have to be very low for good performance of the junction.

The important aspect of this expression is that the I-V behaviour of other types of junctions, such as metal-semiconductor and electrolyte-semiconductor and junctions formed by two different semiconductors can also be described by it.

1.4 PRINCIPLE OF OPERATION OF A P-N JUNCTION SOLAR CELL

Solar cell is an electronic device which converts solar energy directly into electrical energy through the photovoltaic effect. It is a typical semiconductor p-n junction device. The principle of operation of a p-n junction solar cell is illustrated in Fig.1.7. When the light falls on the device, the light photons of certain wavelengths are absorbed by the semiconducting material and electrical

charge carriers, electrons and holes, are generated. These carriers diffuse to the junction where a strong electric field exists. The electrons and holes are separated by this field and produce an electric current in the external circuit. This current, called photo-current, depends on the incident photon intensity and the nature of semiconductors that constitute the junction device. The merit of a solar cell is that it performs this energy conversion from light to electric energy without producing any noise or pollution and with little maintenance.

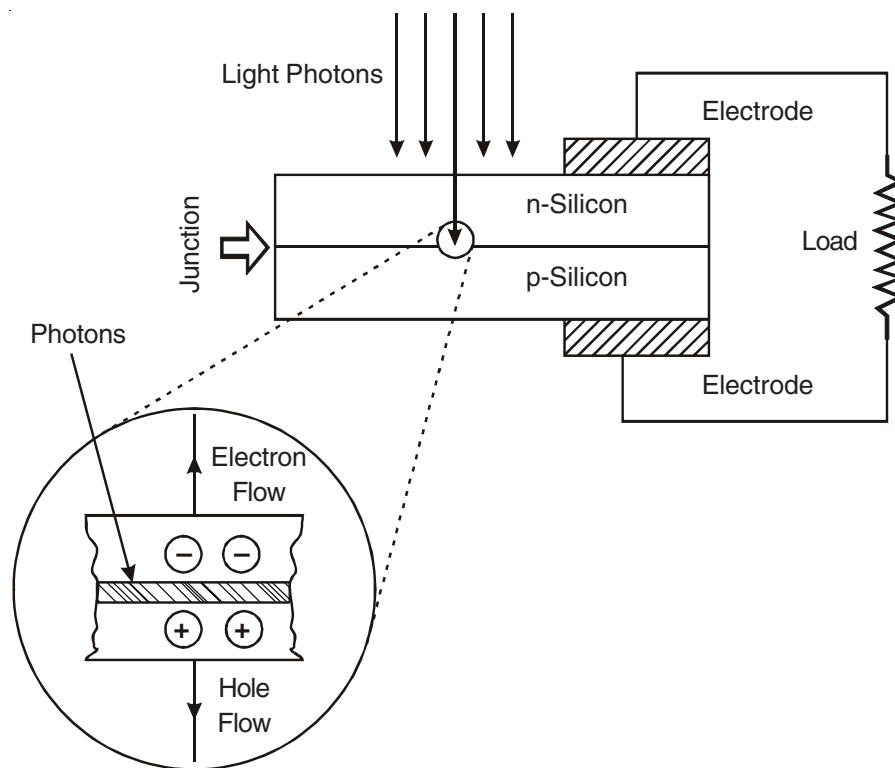


Fig. 1.7 Photovoltaic Effect in a Solar Cell

Fig. 1.8 shows the current-voltage curves, curve 1 represents I-V behaviour with no incident light. Under illumination, a photo-generated current, I_{ph} , flows as reverse diode current, which is linearly dependent on the intensity of incident light.

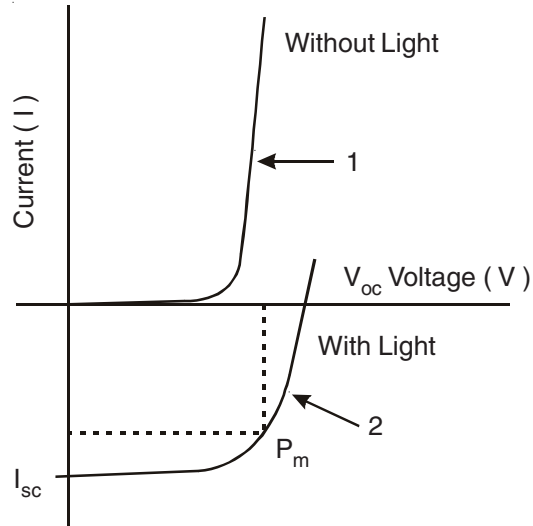


Fig. 1.8 I-V characteristics of Solar Cell

The resultant current is

$$I = -I_{ph} + I_o \left[\exp\left(\frac{qV}{\gamma kT}\right) - 1 \right] \quad \dots\dots\dots (15)$$

and is represented by curve 2.

The measurement of I-V characteristics for a solar cell is given in Annexure 1. The output power in the load R_L is $R_L I_R^2$ and indicates the occurrence of energy conversion (Fig. 1.9).

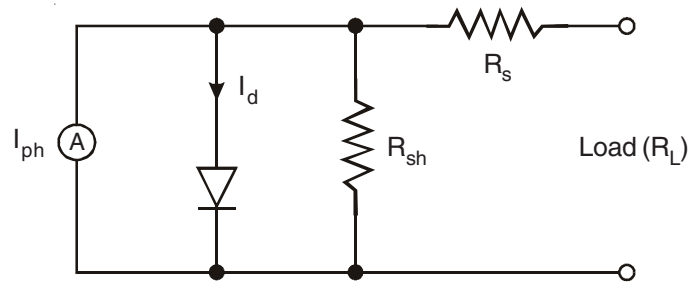


Fig. 1.9 Equivalent circuit of a Solar Cell

If the terminals of the junction are shorted, the power output becomes zero; and by adjusting R_L , an optimum value may be found for maximum output power, P_{max} .

The conversion efficiency, η may be defined as

$$\eta = \left[\frac{\text{Output at optimum operating point}}{\text{Energy input to junction}} \times 100 \right] \dots\dots\dots (16)$$

under certain specified conditions.

Two important parameters - short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) have to be understood at this point. If the terminals of the junction are shorted, no current flows in the junction. When the junction is illuminated, a current called ‘short-circuit current’ flows in the junction from p- to n- side or otherwise depending on which side of the junction, the light is incident. This photocurrent is due to three contributions: holes generated in the n-region, electrons in the p-region and electrons and holes in the depletion region before they recombine.

I_{sc} is a function of cell design and is proportional to photon flux. If the load is an open circuit, the corresponding V_{out} is called ‘open-circuit voltage, V_{oc} ’. I_{sc} and V_{oc} are related to the output power at the ‘optimum operating point’, P_{max} as

$$P_{max} = V_{oc} \times I_{sc} \times FF \dots\dots\dots (17)$$

where FF, the fill factor.

$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}} \dots\dots\dots (18)$$

V_m and I_m are the voltage and current at the optimum operating point. Typically V_m is 75 to 90 percent of V_{oc} ; and I_m is 85 to 99 percent of I_{sc} for silicon.

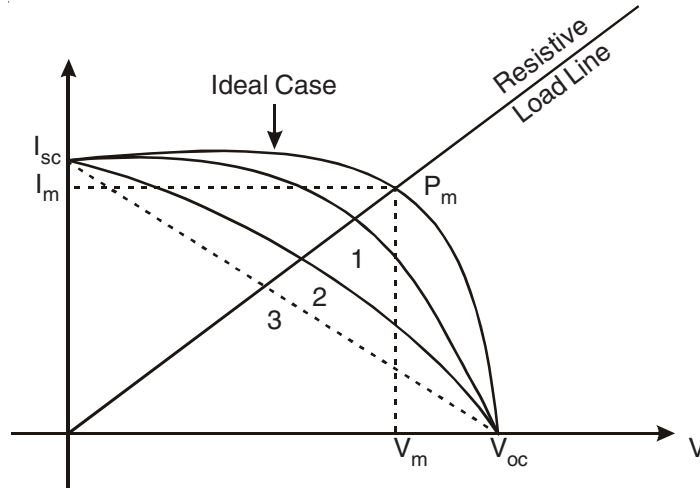


Fig. 1.10 I-V Curves: 1, 2, 3 as R_s is increasing

The efficiency expression becomes

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{\text{Incident Solar Power}} \quad \dots\dots (19)$$

In the actual operation of the p-n junction solar cell, the resistive mechanisms and shunt paths come into play significantly (Fig. 1.9); hence, the current-voltage characteristic departs from the ideal one and the fill factor drops (Fig. 1.10).

The efficiency will be high if I_{sc} and V_{oc} are high and so also FF. It means the dark current must be low. The sharp corner in the I-V characteristic is an indicator of high FF.

In practice, the conversion efficiency of a solar cell is measured under Standard Test Conditions (STC), which include (i) solar irradiance intensity of 1000 watts/m², (ii) AM 1.5 solar reference spectrum, and (iii) temperature of cell, during measurement, of 25 °C.

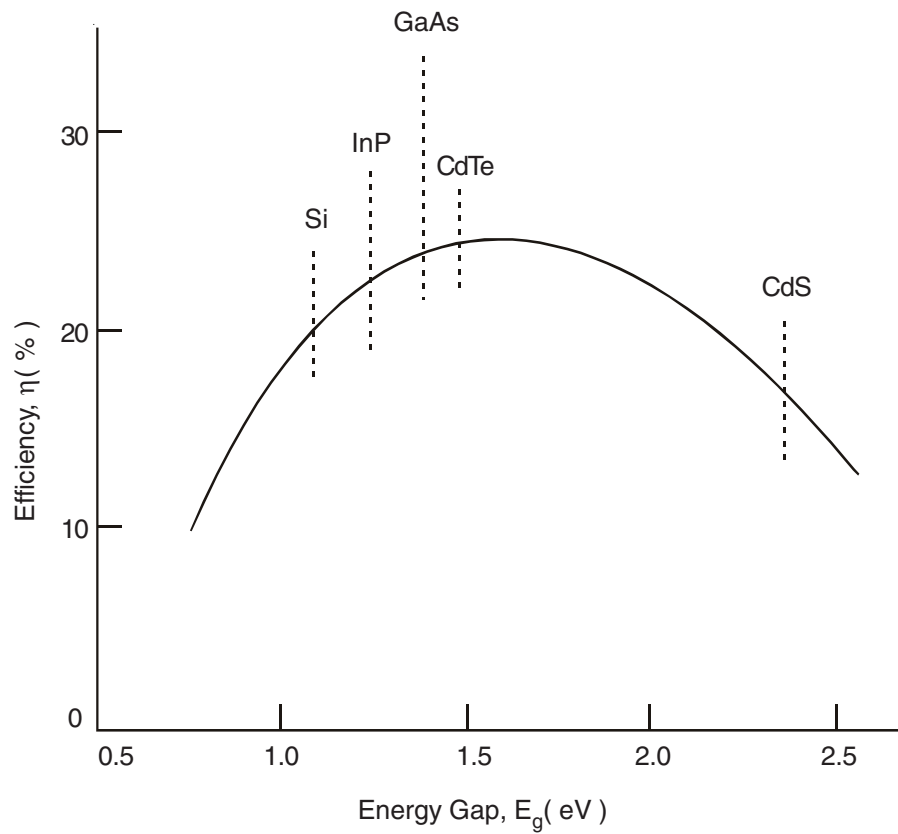


Fig. 1.11 Estimated Efficiency Vs Energy Gap of the Cell Material

1.5 RELATION OF V_{oc} AND E_g

The V_{oc} and E_g are related to a first approximation as

$$V_{oc} = \frac{E_g}{q} \quad \dots\dots\dots (20)$$

indicating that V_{oc} is directly proportional to the band gap energy.

Earlier in Fig. 1.3, it is seen that the current generation rate decreases with increasing energy gap, which means that the cell efficiency reaches maximum at certain range of values of E_g .

It is interesting to study how the change in energy gap influences the energy conversion of a solar cell. Firstly, a larger E_g reduces the reverse saturation current and increases V_{oc} which in turn tends to increase the efficiency. Secondly, a larger E_g means that a fewer photons can be absorbed because only those photons greater than and equal to E_g are absorbed, which in turn decreases the efficiency. The net result of these two opposing effects are shown in Fig. 1.11. The calculated efficiency has a maximum of about 25% at E_g equal to about 1.5 eV and falls off on either side of this value.

The semiconducting compounds, Cadmium telluride(CdTe) and Gallium arsenide(GaAs), Indium phosphide(InP) have E_g around this value. In practice, semiconductors with energy band gaps in the range 1.0 to 1.7 eV are used for maximum efficiency devices/solar cells. These include monocrystalline and multicrystalline silicon($E_g = 1.12\text{eV}$), copper indium diselenide($E_g = 1.05\text{eV}$) and amorphous silicon($E_g = 1.7\text{eV}$).

The silicon-based devices are ‘homojunctions’ (junctions within the same material), whereas many of the compound semiconductor devices are ‘heterojunctions’ (junctions between two dissimilar materials). These generally use n-type wide energy band gap layer to form a junction with the p-type absorber layer. This structure is generally preferred.

The theoretical efficiencies are evaluated by assuming an ideal case of a cell fabricated with well-established processing and manufacturing techniques.

The factors which affect the efficiency of solar cells are dealt in the next chapter.

REFERENCES

1. *Muller, R.S. and Kamins, T: Device Electronics for Integrated Circuits, Wiley-Inter Science, New York (1977)*

BOOKS FOR FURTHER READING

1. **Larry D. Partin:** *Solar Cells and Their Applications*, Wiley-Inter Science, New York (1995).
2. **Richard Bube:** *Photovoltaic Materials*, Imperial College Press, London (1998).
3. **M.A. Green:** *Solar Cells: Operating Principles, Technology and Systems Applications*, Prentice-Hall, (1992).
4. **J. Nelson:** *The Physics of Solar Cells*, Imperial College Press, London (2003).