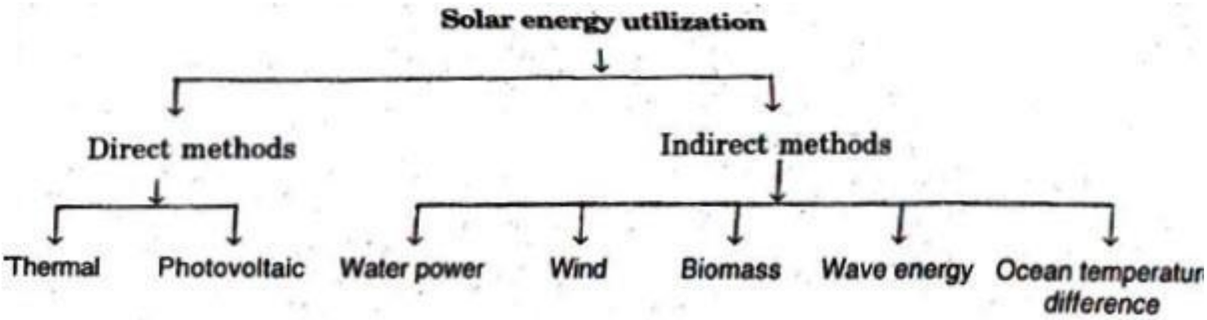
Chapter 3

Photovoltaic systems

3.1 Modes or utilization of solar energy:

The energy from the sun can be used directly or indirectly. The direct method includes: thermal and photovoltaic conversion, while indirect means include use of water power, Winds, biomass, wave energy and temperature difference of ocean.

A broad classification of modes of utilization is as under:



The thermal mode of utilization of solar energy includes the following methods

1. Solar water heating.
2. Solar distillation
3. Solar drying of agriculture and animal product
4. Heating and cooling the house
5. Solar cooker
6. Solar water pumps
7. Solar furnace
8. Food refrigeration
9. Solar pond and steam generator
10. Solar green houses

3.2 PHOTOVOLTAIC PRINCIPLE:

Photovoltaic conversion is direct method of utilization of solar energy. It is the most useful way of harvesting solar energy by directly converting it into electricity; the cells used in photovoltaic conversion are called solar cells. When solar radiation falls solar cells, it is directly converted into d.c. electricity. This effect is called photovoltaic effect.

The photovoltaic effect can be observed in nature by variety of materials. But the materials that have shown the best performance in sunlight are the ‘semiconductors e.g. germanium and silicon. These are the elements having resistivity of the order of 10^4 or 10^5 Ω m which lies between good conductor and insulator.

In an intrinsic semiconductor such as silicon, each one of four valence electrons of atom is tied in covalent bond and there are no free electrons at absolute zero. If material of pentavalent impurity like arsenic or phosphorus is doped with silicon, there will be excess of electrons and it will become n-type semiconductor. When impurity like boron is doped with silicon, there will be deficiency of electron leading to p-type semiconductor. This deficiency is expressed in terms of excess of holes free to move. When p-type and n-type semiconductors are joined together, p-n junction is formed (See Fig. 3.2.1).

Depletion Region or window :

Consider a p-n junction as shown in the Fig. 4.6 below :

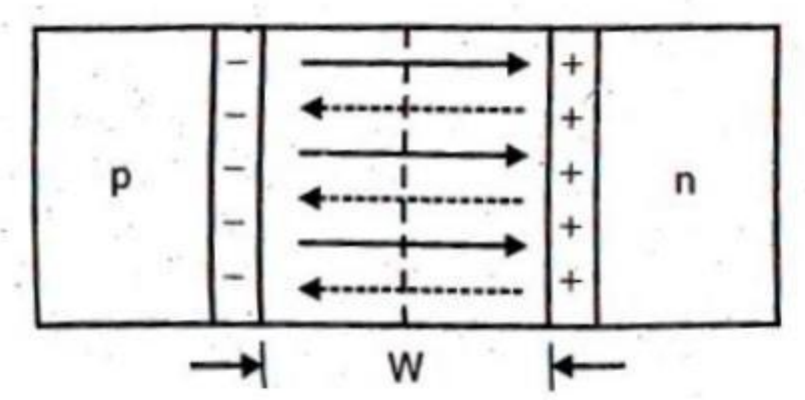


Fig. 3.2.1 Depletion region

when the junction of p and n type semiconductor is formed the mobile charge carriers holes and electrons, due to their high concentrations in p and n regions respectively, diffuse into opposite sides at the junction. Due to recombination of holes and electrons near the junction, there is the accumulation of positive charge at border of n region and negative charge at border of p region. Thus a dipole layer exists at p-n junction and these bound charges do not allow other majority carriers to cross the junction. Hence a barrier region is formed near the. junction. In this region, there are no holes on p-side and no electrons on n-side. Thus the region is devoid of free charge carriers. This region is called "Transition" or Depletion region" or "Window". It is represented by W.

Photovoltaic effect: Consider a p-n junction diode as shown in the Fig. 3.2.2 below :

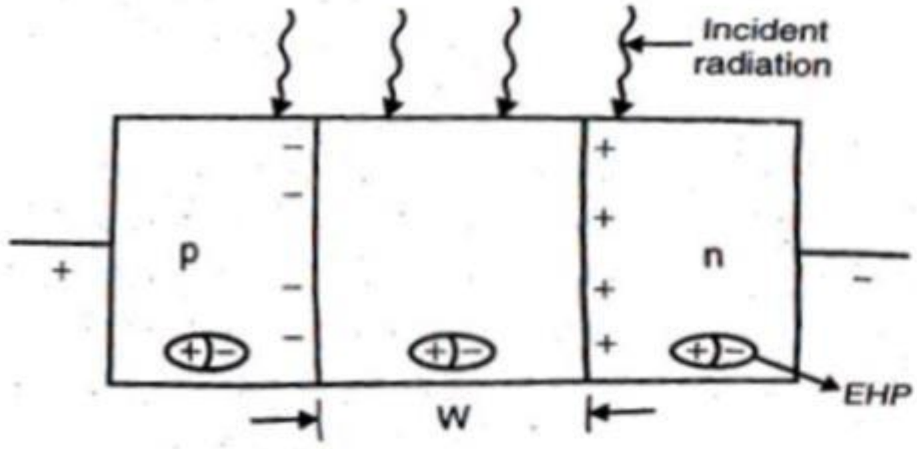


Fig. 3.2.2 Photo voltaic effect

When solar (radiations fall on this junction diode then if the incident photon has sufficient energy to knock out the electron from covalent bond, the electron-hole pair (EHP) is created. If EHP is created in the p-region then current cannot be set up across junction due to bound charges at the boundary of depletion region i.e. at window. Similar situation exists if EHP is created in the n-region due to bound positive charge.

But when EHP is created in the depletion region then the holes are attracted towards p-region and electrons are attracted towards n-region. Thus an electric current is set up through the diode. As a result a voltage drop is developed across the semiconductor due to incident solar radiations In this way the p-n diode is used as a device to collect solar energy and convert it into electricity. When a load is connected across these polarities, an electron current flows through it and useful power is available across the external load.

This is p-n diode solar cell. Types of Solar Cells:

(I) p-n Junction solar cell:

The first solar cells were made of silicon in the U.S.A. in 1954. Silicon cells are the only cells having commercial status. Conventional silicon cells are then wafers about 300 µm in thickness and 3 to 6 cm in diameter sliced from a single crystal of n-type and p-type doped silicon. A shallow junction is formed at one end by diffusion of the other type of impurity. Metal electrodes made from Ti - Ag solder are attached to the front and back side of the cell. On the front side, the electrode is in the form of a metal grid with fingers which permit the sunlight to go through, while on the back side, the electrode completely covers the surface. An anti reflection coating of S_iO having a thickness of 0.1μm is also put on the top surface as shown in Figure 4.2.3.

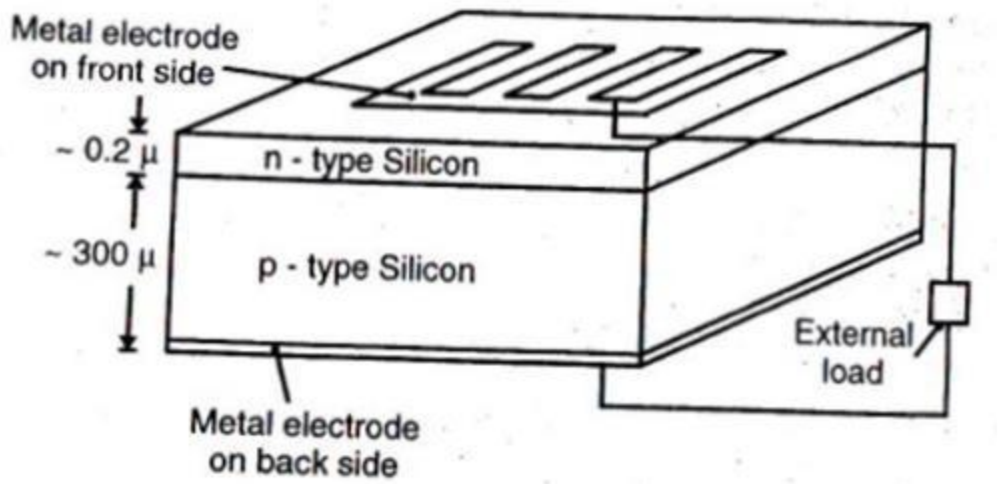


Figure 4.2.3: Diagram of a solar cell

When radiation falls on in case of p-n junction solar cell, the width of depletion region (window) is very small of the order of 10^{-4} to 10^{-5} cm. Due to this very small width, small amount of solar radiations are converted into electricity. This limitation is overcome by increasing the Width of depletion region of diode.

(2) p-i-n diode solar cell:

The increase in width is achieved by inserting a single crystal of intrinsic material, i.e. a .pure crystal having no doped (impurity) atoms, in the depletion region as shown in the Figure 4.2.4.

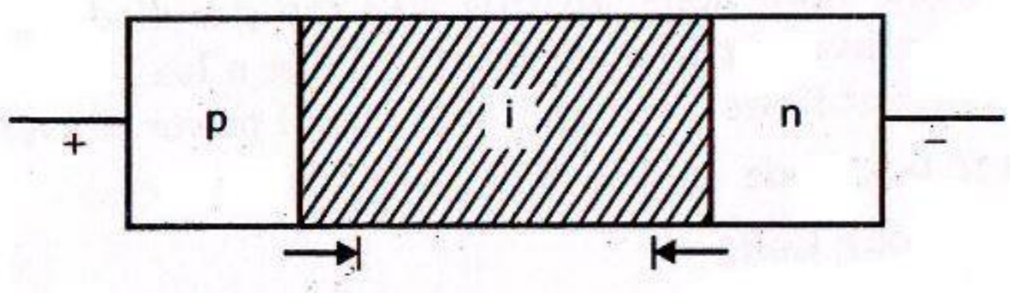


Figure 4.2.4: p-i-n diode solar cell

Due to increased width of depletion region, more solar radiations are collected and converted into electricity. The intrinsic material also reduces the response time of solar cell and makes it very fast in action i.e. having quicker response.

Action in intrinsic material;

In ‘i’ region of intrinsic material there are no doped atoms, so the electrons and holes not suffer any decrease in their velocity during their movement towards the boundaries of depletion region. As a result solar cell becomes quite fast giving the response time of the order of 10^{-6} sec.

This solar cell is also homojunction solar cell, Silicon is the most commonly used material for solar cells due to its stability, reliability consideration and cost of production which is low. Silicon is used in the form of polycrystalline thin film or the wafers or a single crystal. The materials like Ga, As, CdS or $Cu_2 S$ are also used for manufacturing of solar cells.

Some other solar cells:

(1) Cadmium Sulphide solar cell: In this cell the junction is of cadmium sulphide and copper sulphide. Such a cell is known as heterojunction solar cell. In this cell very thin layers of polycrystalline material is used, so very low material consumption and low cost due to polycrystalline layer than for monocrystalline layer. The open circuit voltage is in the range 0.4 to 0.5 volt which is lower than silicon solar cell. This cell has stability up to 90°C and hence future prospects for this cell for large scale electricity production are promising.

(2) Gallium Arsenide solar cell: This is also homojunction solar cell. In this cell when polycrystalline thin films are used performance is very poor, but with monocrystalline thin films it has high efficiency. Monocrystalline thin layer in very pure form hence costs very high. These layers have very high absorption co-efficient for visible light. All visible light is absorbed even in the layer of about 1 μm thickness. Its open circuit voltage is slightly less than 1 volt which is appreciably higher than that silicon solar cell.

This cell has better performance at temperature above 100°C.

(3) Indium Phosphide solar cell: It is made by epitaxial growth of n-type CdS layer on

p-type single crystal of indium phosphide. It is a heterojunction solar cell. The performance of solar cell is affected by (i) humidity, (ii) temperature variation, (iii) rain, (iv) corrosion due to moisture.

I-V. Characteristics of Solar Cell:

A typical current-voltage (I-V) characteristic of p-n silicon solar cell is shown in the Figure 4.2.5 below.

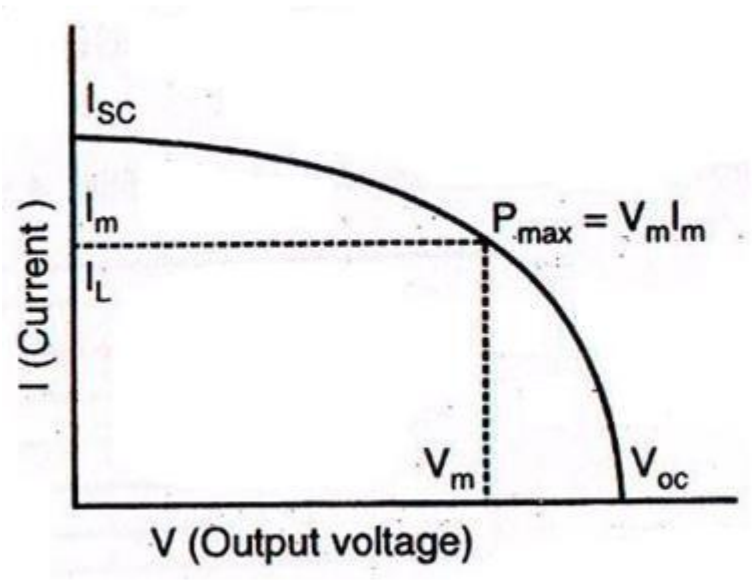


Figure 4.2.5: I-V characteristic of silicon solar cell

Generally, the silicon solar cells employed for terrestrial applications are round wafers of 5 cm diameter and thickness of 0.3 to 0.5 millimetres. This cell delivers in full sun and at room temperature a power of 0.2 watt at 0.45 volt. For, higher power or higher voltage, number of cells must be assembled. e.g. to double the voltage, two –cells are connected in series and to double the power at constant voltage, two cells are connected in parallel. For assembly of cells matching the electrical characteristic is important. For parallel assembly same open circuit voltage and same maximum power point voltage is necessary and for series assembly same short circuit current and same maximum power point current is necessary.

The short circuit current I_{SC} and open circuit voltage V_{OC} are the output parameters of solar cell.

The current voltage (I-V) characteristic of solar cell curve Fig. 4.2.5 shows that the maximum voltage is obtained across solar cell when no current is drawn from the cell. This occurs when the external circuit is open. This voltage is called open circuit voltage and denoted by V_{OC}. Similarly current delivered by solar cell is maximum when there is no resistance in the external circuit. This occurs when-the solar cell is short-circuited. This current is called short circuit current and denoted by I_{SC}. The product V_{OC} and I_{SC} is the ideal power of the solar cell.

The co-ordinates of points on the I-V curve at which maximum power is drawn from the solar cell are V_m and I_m. .Thus maximum useful power is $V_m I_m$. The maximum useful power is given by the area of the largest rectangle under I-V curve (See Fig. 4.2.5). Typical values of V_{OC} and I_{SC} for a silicon cell are given below :

V_{OC} – 450 to 600 mV

I_{SC} -30 to 50 mA

Fill factor (FF) of solar cell:

It is defined as the ratio of the maximum useful power to the ideal power,

$$\textbf{F.F.} = \frac{\textbf{Maximum useful power}}{\textbf{ideal power}}$$

$$\textbf{F.F.} = \frac{Vm \times Im}{V_{OC} \times I_{SC}}$$

The fill factor is always less than one and for solar cells of reasonable efficiency, it has a value in the range 0.7 to 0.85. Ideally, it is a function of open circuit voltage V_{OC} only.

I-V characteristics of solar cell under dark and illuminated conditions:

Silicon solar cells show the response to the radiations of wavelengths less than 11500A°.

The I-V characteristics of solar cell can be studied under following two conditions:

(1) Dark condition: When no solar radiations are incident, it is called “Dark condition".

(2) Illuminated condition: When solar radiations are incident, it is called “Illuminated condition".

Let us analyse the I-V characteristics of p-n junction solar cell when it is under (i) dark condition and (ii) illuminated condition.

The basic requirement for photovoltaic conversion is an electronic asymmetry in the structure of a semiconductor as shown in Fig. 4.2.6.

This figure shows that a p-n junction possesses required asymmetry, n-type regions have large electron densities but small hole densities. Hence electrons flow quickly through such material but holes find great difficulty. In p-type regions, exactly the opposite is true.

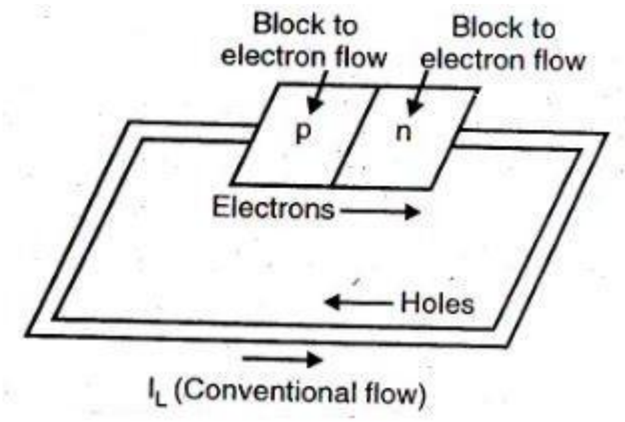


Fig. 4.2.6 Asymmetrical properties of a p-n junction diode

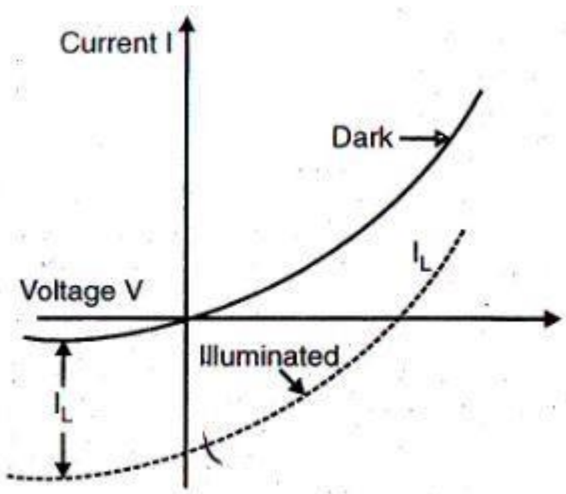


Fig. 4.2.7: Superimpositions of the light generated current on normal rectifying current-voltage characteristics of the diode. This results in an operating region in the fourth quadrant where electrical power is extracted from the solar cell.

When such junction is illuminated, excess electron hole pairs are generated by light throughout the material. If we short the illuminated p-n junction, a current' will flow in the Short-circuiting wire. The light generated current is superimposed on the normal diode rectifying characteristics which give an operating region in the fourth quadrant where power can be extracted from the solar cell as shown in Fig. 4.2.7.

Efficiency of the Solar Cell:

The energy conversion efficiency (η) of a solar cell is defined as maximum output power extracted from solar cell divided by the, total input power given to the solar cell i.e. total power in ‘the incident solar radiations. Thus,

$$\text{efficiency}(\eta) = \frac{(P_{output})_{max}}{(P_{input})}$$

$$\eta = \frac{V_m \times I_m}{(P_{input})}$$

But $V_m \times I_m = (FF) \times V_{oc} \times I_{sc}$

$$\eta = \frac{(FF) \times V_{oc} \times I_{sc}}{(P_{input})}$$

The efficiency of solar cell is very low. The best silicon solar cell produced in the laboratory today has an efficiency of about 20 %. The commercial solar cells have the efficiencies between 12 % and 14 %.

Dependence of efficiency on Band gap energy of semiconductor:

In case of solar cell, the reverse saturation current I_o is given by,

$Io = 1.5 \times 10^5 e^{-Eg/KT}$ ..... (1)

where Eg is band gap energy and kT is thermal energy. I_o can be written as

$$I_o = \frac{1.5 \times 10^5}{e^{-Eg/KT}}$$

The above expression for I_o gives that larger the band gap energy, smaller is the I_o,

When I_o is smaller, V_{OC} is large and hence efficiency will be large. Thus large E_g gives large efficiency. But increase in V_{OC} causes decrease in I_{SC}. In the expression of efficiency, the numerator is the product of V_{OC} and I_{SC}. So the trend of efficiency will be first it will increase with increase in E_g and then it will decrease. This trend is shown in the graph below (Fig. 4.2.8).

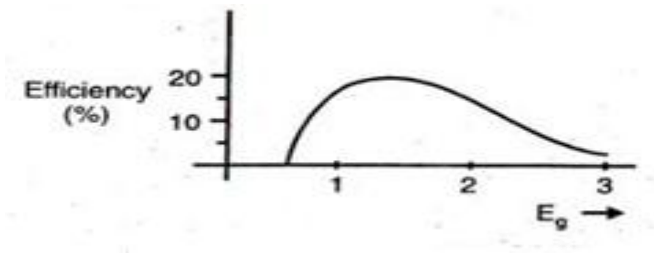


Fig. 4.2.8 variation of efficiency with band gap energy

Applications of Solar Cell:

(1) The solar cells (also called photovoltaic devices) supply power ranging from fraction of a watt e.g. in calculators and watches to hundreds of kilowatts e.g. in large arrays connected to electricity grids. Electricity grid is-the system supplying bulk electrical power to cities, industries, etc.

(2) An assembly of large number of solar. cells in desired combination depending on the purpose of either large voltage or current is called solar panel or array. A solar panel produces electricity in the D. C. form. This electrical energy can be used for hundreds of 5 applications. Even though, the power output of solar panel varies with the time of day, season, environmental conditions, etc. the solar panels constitute a reliable and convenient way of generating electric power. The solar panels are very much useful in remote and isolated locations or energy requirements of rural communities where it is often very expensive to erect maintain electricity transmission lines. The solar cells are a must in situations where it is desirable to have power on highly reliable basis e.g. in the communication systems in satellites.

(3) Photovoltaics are used for water pumping, lighting, communications, radio and TV receivers, calculator functioning, wrist watches, power for light houses, off-shore oil Platforms, etc. Solar powered aircraft and automobile are the unusual applications. Pumping of water for irrigation and drinking purpose is the most important application in, every developing country. Next comes lighting in rural communities and battery charging.

(4) The widespread use of solar cells in many applications is hampered by the high cost of its production. The cheap and reliable way of producing electricity is necessary for hundreds of applications. But this will however burden scientific and engineering capabilities to the maximum before becoming a reality.

Solve problems:

1. A photovoltaic system is installed for supplying drinking water in a village. Calculate the power output from array of the 24 modules having following specifications:

   1) Incident solar flux = 0.945 Kw/m^2 2)
   Cell size = 0.104 x 0.104 m
   3) Conversion efficiency = 12.8 %
   4) Number of cells = 36

   Solution: Power output form array = (Incident solar flux)x(Cell area)x(Conversion efficiency)

$= 645x(0.104x0.104)x\ 0.128$

$= 1130.4$ W

2. What is the wavelength at which si1icon cell start to absorb light ?

(Given : Eg = 1.1 eV, Planck constant = 6.63 X 10^{-34} Js)

Hint: $E=h/\upsilon = hc/\lambda$ (Ans. 1.1)

Solution: Eg = 1.1 eV, Planck constant = 6.63 X 10^{-34} Js 1 ev = 1.6 x 10^{-19} J, C= 3x 10^{8} m/s

$$E=h/\upsilon = hc/\lambda = (6.63 \text{ X } 10^{-34} \text{ x } 3\text{x } 10^{8}) / (1.1 \text{ x } 1.6 \text{ x } 10^{-19})$$

$$= 11.30 \text{ x } 10^{-7}$$

$$= 113.0 \text{ x } 10^{-8} \text{ cm} = 113 \text{ x } 10^{-10} \text{ m}$$

$$= 113 \text{ A}^{o}$$

1. Calculate the input power of solar cell

Given : η = 12 % = 0.12 , V_{oc} = 4.50 mV = 4.50 x 10^{-3} V, I_{sc} = 30 = 30 x 10^{-3} A, f.f. = 0.7 , P_{input} = ?

$$\eta = \frac{V_{oc} \text{ x } I_{sc \text{ x}} \text{ f.f.}}{P_{input}}$$

$$P_{input} = \frac{V_{oc} \text{ x } I_{sc \text{ x}} \text{ f.f.}}{\eta}$$

$$P_{input} = \frac{4.50 \text{ x } 10^{-3} \text{ x } 30 \text{ x } 10^{-3} \text{ x } 0.7.}{0.12}$$

$$= 787.5 \text{ x } 10^{-6}$$
$$= 0.7875 \text{ x } 10^{-3} \text{ W.}$$

1. Calculate the fill Factor (F.F.)of solar cell by using following data.

Given : V_{oc} = 600 mV = 600 x 10^{-3} V, I_{sc} =50 = 50 x 10^{-3} A, Vm = 500 mV = 500 x 10^{-3} V ,

Im =40 mA = 40 x 10^{-3}A , F.F.= ?

$$F.F. = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

$$= \frac{500 \times 10^{-3} \text{ X } 40 \times 10^{-3}}{600 \times 10^{-3} \text{ X } 50 \times 10^{-3}} = \frac{20}{30}$$

$$= 0.66$$

2. Calculate the power output form array consisting of 20 modules and 30 cells having area of 0.1 m2 if conversion efficiency is 0.128 (Incident flux = 900).

   Solution :

   Power output form array = (Incident solar flux) x (Cell area) x (Conversion efficiency)

   = 900 x (0.1)x 0.128

   = 11.52 W

QUESTIONS AND EXAMPLES

1. Explain photovoltaic effect.
2. What is solar cell ? List different types of solar cell.
3. Define the terms : Fill factor and efficiency of solar cell.
4. Sate the limitations of Photovoltaic cell efficiency.
5. Explain I-V characteristics of solar cell. Define fill factor.
6. Sate advantages of photovolataic system.
7. State different types of solar cells. Explain I-V characteristics of solar cell.
8. What are different materials used in solar cell fabrication?
9. What are disadvantages of photo voltaic system?
10. Sate different types of solar cell.
11. Discuss parameters affecting efficiency of solar cell in detail.
12. Write a note on thin film solar cell.
13. Explain the photovoltaic principle. Describe a basic photovoltaic system for power generation.
14. Explain PV system for street light.

15. Write a short note on photovoltaic panels.
16. Explain I-V characteristics of solar cell and hence define fill factor (F.F.) and maximum conversion efficiency.
17. What are advantages of photo voltaic system?
18. What are main applications of solar photovoltaic system? Describe one briefly.
19. Write a short note on silicon solar cell.
20. What is solar module?
21. Discuss parameters affecting efficiency of solar cell in detail.
22. Calculate the fill factor of solar cell the using following data:

    Voc = 600 mV, ISC = 50 mA, Vm = 500 mV, 40 mA (Ans. 0.666)

23. Calculate input power of solar cell using the following data :

    Efficiency of cell = 12 % - , Voc = 450 mV, ISC =- 30 mA , Fill factor = 0.7 (Ans. 9.45 mW)

24. What is the wavelength at which si1icon cell start to absorb light ?

    (Given : Eg = 1.1 eV, Planck constant = 6.63 X 10^{-34} Js)

    Hint: $E=h/\upsilon =hc/\lambda$ (Ans. 1.1)

25. Compute the system output and current of a PV array for 100 watts load needed for 24 hours at 24 volt at New Delhi (Φ = $28^{o}35'$) Mean horizontal isolation from standared map H_o= 5.4 kwh/m^2.