CHAPTER II

CHAPTER - II

Theoretical Background : Theory of Solar Cell

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2.1 Introduction :

Considerable interest has recently been developed for the large scale utilization of solar energy converters[1-4]. The main areas of interest are: solar heating and cooling of buildings, solar thermal conversion, bioconversion etc.

For solar heating and cooling of buildings, the solar thermal energy absorbed in solar thermal collectors is directly used for heating and cooling. In solar thermal energy conversion, the heat from the thermal collector is used to run heat engine for electricity generation. Bioconversion includes the conversion of waste, cultivated organic materials, or water, to gaseous, liquid or solid fuels, using bio-organisms, photochemical processes, or biophotochemical methods.

Solar cell converts sunlight directly into electricity by means of photovoltaic effect; which is the generation of electromotive force by absorption of ionizing radiation. This effect was first recorded in 1839 by Becquerel, who detected photovoltage between AgCl and Pt electrodes immeresed in an electrolyte. Adams and Day were the first to observe the photovoltaic effect in solid selenium. Number of other solid state workers including Longe, Grandahl and Schottky did pioneering work in selenium and cuprous oxide photovoltaic cell. Photovoltaic conversion process has been demonstrated in small systems for special applications both on ground and in space[5-7]. Single crystal solar cell[8-9] have been produced but the high production cost of such devices restricts their use for the terrestrial applications. In recent years, semiconductor electrolyte cells have been attracting a great deal of interest in the field of energy conversion, as their low cost and moderate efficiency.

2.2 Types of solar cells :

Solar cell is the semiconductor device which converts the radiant energy into the form of electrical energy. Solar cells can be grouped mainly into the following four categories namely :

1) Semiconductor-semiconductor junction cells,
2) Semiconductor-metal junction cells,
3) Semiconductor-liquid junction cells,
4) MIS, SIS cells.

2.2.1 Semiconductor-Semiconductor Junction Cells :

There are two types of S-S junction cells namely homojunction and heterojunction cells.

The homojunction cell normally consist of a shallow p-n junction formed either by diffusion of a dopant into a monocrystalline semiconductor substrate or by growth of an epitaxial layer on to the substrate. Silicon and gallium arsenide are two common materials used, with the diffused silicon cell. Fig. 2.1(a) and (b) shows the structure and the energy band diagrams of a typical p-n homojunction cell.

A heterojunction cell consists of the interface between two dissimilar semiconductors. Depending on nature of interface, the heterojunction cells can further be classified as abrupt or graded. Heterojunctions are fabricated by growth or deposition of one semiconductor onto the other. The energy band profile of n-CdS/P-CdTe heterojunction at thermal equillibrium

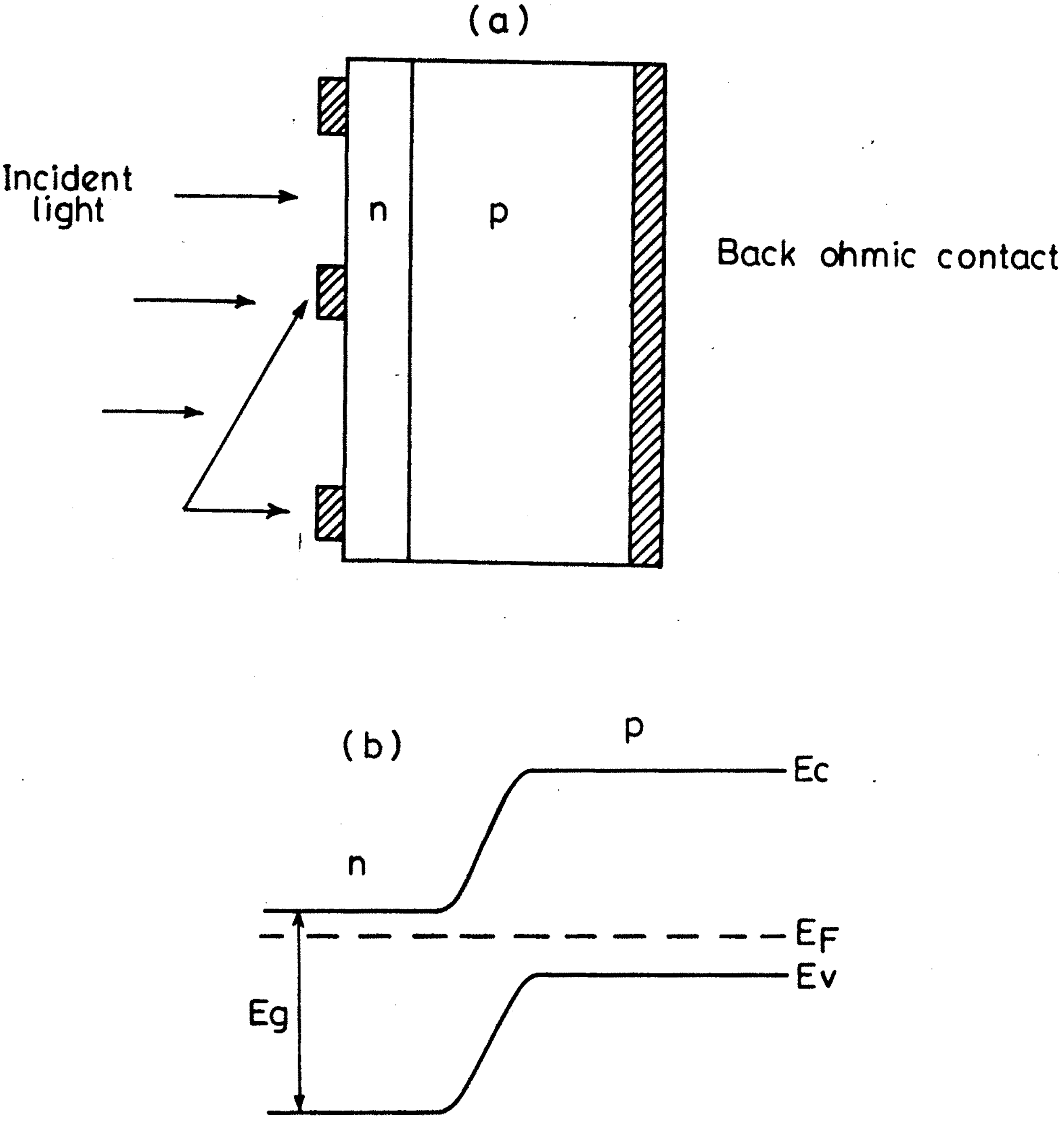


Fig. 2·1 (a) Structure of p-n homojunction solar cell.
(b) Energy band diagram of p-n homojunction solar cell.

and zero bias is shown in Fig.2.2(a)(b) before and after formation of abrupt heterojunction. Each semiconductor is characterised by its electron affinity x, energy band gap E_g and work function The CdS/Cu_2S cell is a common example of this type of cell.

2.2.2 Semiconductor-Metal Junction Cells :

Semiconductor-metal junction cells, are probably the simplest of all types to fabricate, requiring only an ohmic contact at the back and a semi-transparent metal at the front, along with the usual contact grid pattern. The transparent metal film is normally evaporated onto the semiconductor surface and film of about 100 A^o thickness yield transmission of about 60% with sheet resistivities of 5-50 ohms/sq.cm. Fig. 2.3(a) and (b) shows structure and band diagram of Schottky barrier solar cell.

2.2.3 Semiconductor-Liquid Junction Cells :

Semiconductor-liquid junction cells have been attracting a great deal of interest in the field of solar energy conversion as it converts light energy into electrical energy through the use of ECPV cells. It essentially consist of a semiconducotr photoelectrode and a metallic counter electrode dipped into an electrolyte.

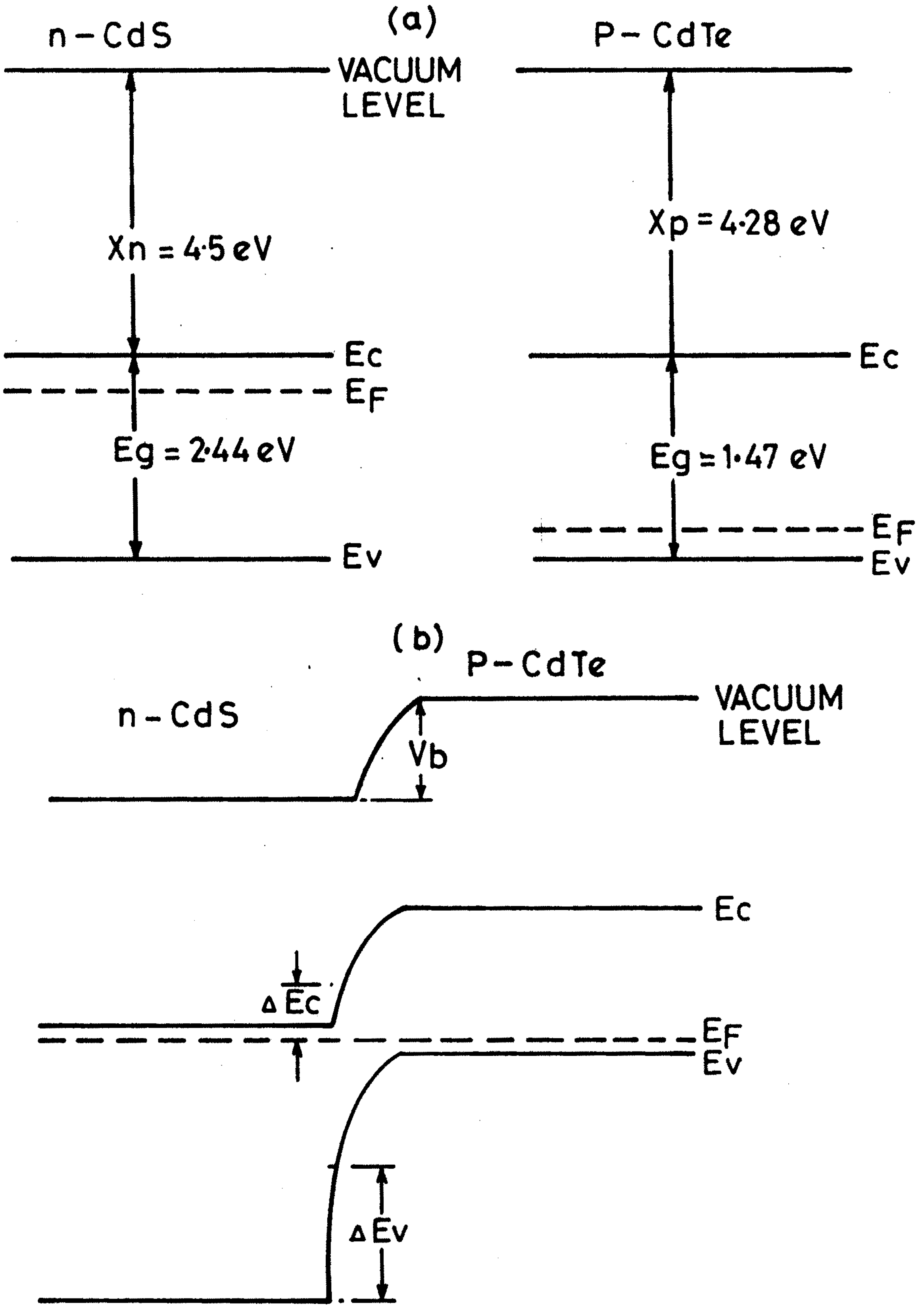
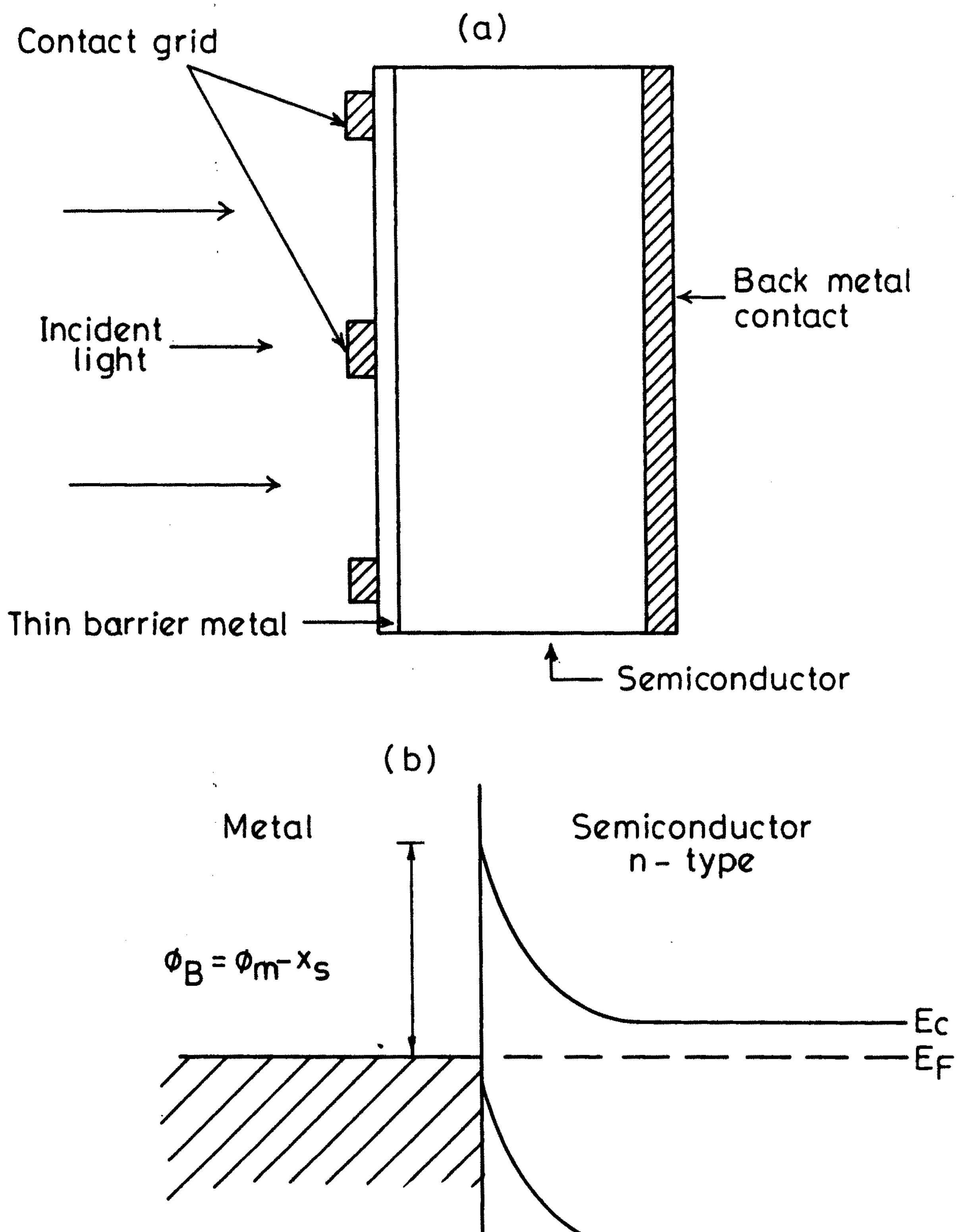


Fig. 2·2 Energy band profile of n-CdS/P-CdTe heterojunction at thermal equillibrium and zero bias a) before and b) after the formation of an abrupt heterojunction.



ϕ_B = Schottky barrier hight.
ϕ_m = Work function of metal.
x_s = Electron affinity of semiconductor.

Fig. 2·3 (a) Structure of Schottky Barrier solar cell.
(b) Band diagram of Schottky Barrier solar cell.

Though the semiconductor-liquid junction cells are superior to p-n junction cells in many respect, there are two major problems associated with semiconductor-liquid junction cells namely,

i) The photocorrosion that occurs when semiconductor immersed in an electrolyte is subjected to illumination.

ii) Overvoltage.

2.2.4 MIS and SIS Solar Cells :

The most common way of forming a solar cell is to create a p-n junction by high temperature diffusion, where the conductivity type of the base semiconductor is changed to opposite type. One of these techniques consist of inducing a conductivity type change at the surface of a semiconductor by the application of an ultra thin metal or a relatively thick transparent (wide band gap) conducting semiconductor rely on thin interfacial layer (10-30 A^o) between the top "inducing" contact (metal or conducting semiconductor) and the base semiconductor. This interfacial layer is generally an oxide or some other compound which is normally an insulator in its bulk form. Hence these cells are referred to as metal-insulator-semiconductor (MIS) or semiconductor-insulator-semiconductor (SIS) solar cells. Fig. 2.4 represent structure of MIS or SIS solar cell with thin interfacial layer.

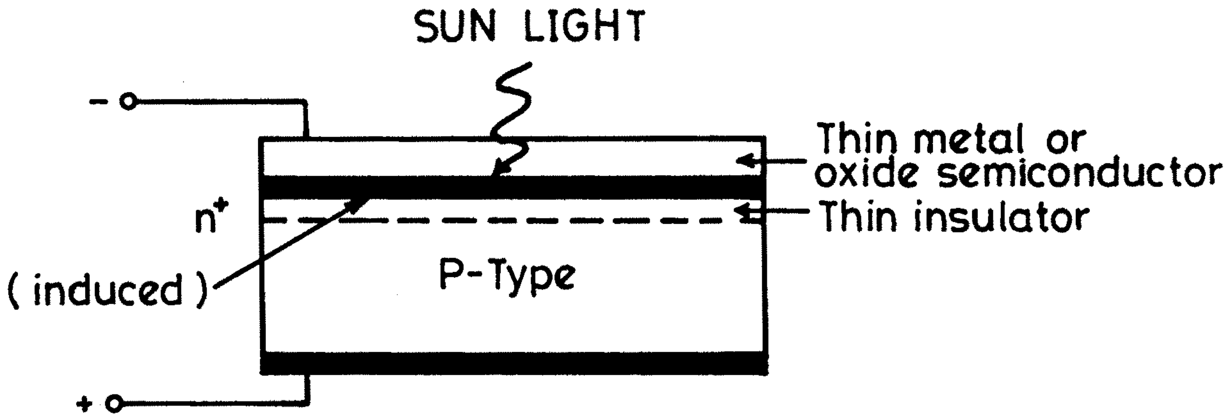


Fig. 2·4 Structure of MIS or SIS solar cell with thin interfacial layer.

2.3 Electrical Characteristics of Solar Cells

2.3.1 Equivalent circuit :

By connecting a load across the terminals of a solar cell a current I_L can flow through the load and develop a voltage V_L across it. The values of I_L and V_L depend on the nature of the load, photogenerated current I_{ph} and the properties of the diode. These relationships can be established by reference to the simple equivalent circuit as shown in fig. 2.5. The photocurrent I_{ph} is represented by a current generator and its magnitude depends on the wave-length and intensity of the incident light; optical absorption co-efficient of the solar cell material, the junction depth, the width of the depletion region and the lifetime and the mobilities of the carries on both sides of the junction. The polarity of the output photo-voltage V_L is such that the diode is in forward bias condition. The current flowing through the diode is represented by I_d and is given by

$$I_d = I_o \left[\exp \frac{eV_L}{nkT} - 1 \right] \qquad \ldots \qquad (2.1)$$

where

I_o is the reverse saturation current

k is the Boltzman constant, and

n is the junction ideality factor.

Shunt resistance paths are represented by R_{sh}; they can be caused by surface leakage along the edges of the cell, by

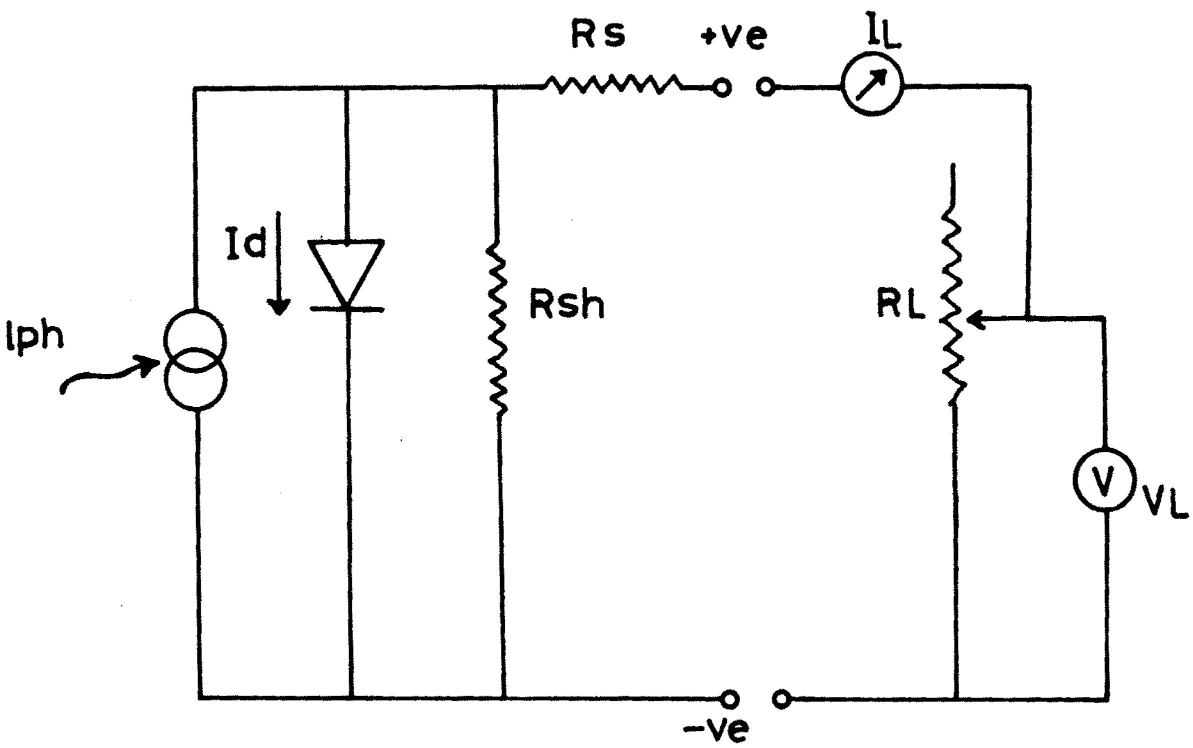


Fig.(2·5) Equivalent circuit of a solar cell diffusing spikes along dislocations or grain boundries. The series resistance, R_s, can arise from contact resistances to the front and back, the resistance of the base region itself. The load resistance is represented by RL and it is desirable to choose its magnitude such that the maximum power is extracted from the solar cell. From the equivalent circuit of fig.2.5 a relation, can be written, between output photo-current I_L and the output photovoltage V_L as

$$I_L \left(1 + \frac{R_s}{R_{sh}}\right) = I_{ph} - \frac{V_L}{R_{sh}} - Id \qquad \ldots \qquad (2.2)$$

Current-voltage characteristics for solar cells can be obtained by three different methods namely

i) Photovoltaic output with constant illumination.
ii) Photovoltaic output with variable illumination.
iii) Diode forward characteristics without illumination.

2.3.2 Photovoltaic output with constant illumination :

This is the most commonly used method, applies a fixed illumination, usually of known intensity, and a resistive load which is varied between short circuit and open circuit conditions, while measuring the voltage across the solar cell terminals and the current out of these terminals. Fig.2.5 shows the circuit diagram for this type of measurement including the generally applied equivalent circuit diagram for the solar cells. The I-V characteristic obtained in this manner is called "Photovoltaic output characteristic". For an ideal solar cell the shunt resistance is very high and hence its contribution in I-V characteristics can be neglected. The photovoltaic output characteristic is described by

$$I_L = I_o \left[\exp\left(\frac{e}{nkT} (V_L - I_L R_s) \right) - 1 \right] - I_{ph} \qquad \ldots \quad (2.3)$$

Since a solar cell acts as a generator, the I-V characteristic is obtained in the forth quadrant of the I-V plane.

2.3.3 Photovoltaic output with variable illumination :

Fig. 2.6 shows the circuit diagram for this type of measurement. It consists of a switch, a high resistance voltmeter and low resistance current meter. Solar cell is illuminated with variable light intensity. The amount of illumination need not have to be known, if the value of the light generated current I_{ph} can be determined. This condition is fulfilled when R_s is sufficiently small.

The short circuit current, I_{sc} and the open circuit voltage, V_{oc} are measured for every light intensity setting. Each pair of corresponding I_{sc} and V_{oc} value is plotted as one point in the first quadrant of the I-V plane and the series of measurements at different intensities give a curve similar to that of the forward bias I-V characteristic of a solar cell in dark. The I-V curve obtained by this method

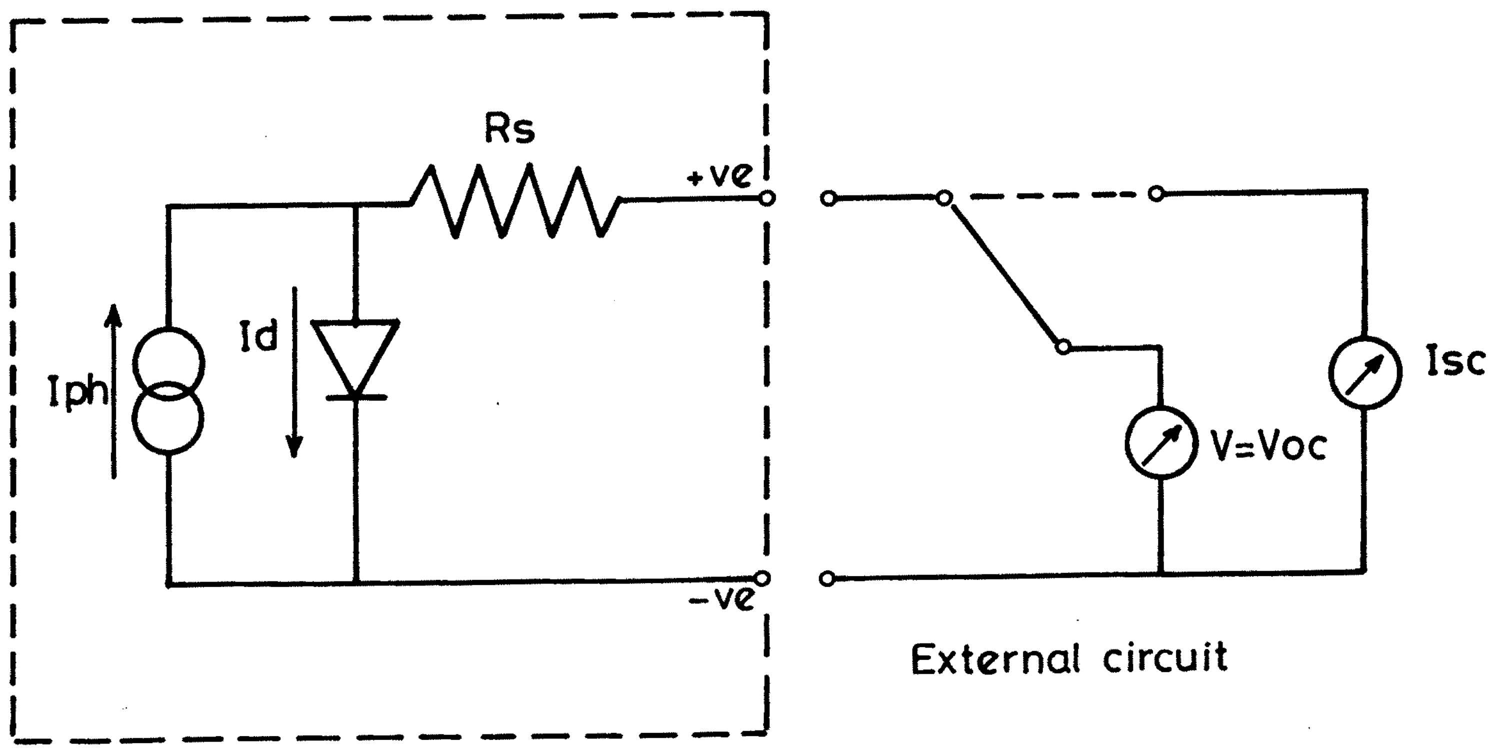


Fig. 2·6 Circuit diagram for photovoltaic output with variable illumination.

is described by

$$I_{ph} = I_{sc} = I_o \left[\exp \left(\frac{e}{nkT} V_{oc} \right) - 1 \right] \quad \ldots \quad (2.4)$$

2.3.4 <u>Diode forward characteristics in dark</u> :

This method tests the solar cell like diode in dark by applying external d.c. power supply in the forward bias condition. The I-V characteristics obtained by this method falls into the first quadrant of the I-V plane. It is described by

$$I = I_o \quad \exp \left[\frac{e}{nkT} (V - I R_s) \right] - 1 \quad \ldots \quad (2.5)$$

The current voltage characteristics of a solar cell obtained from the above three methods are shown in fig.2.7 with the help of equation 2.3 a transition.

$$I = I_o \quad \exp \left[\frac{e}{nkT} (V_L - I_L R_s) \right] \quad \ldots \quad (2.6)$$
$$= I_{sc} + I_L$$

has, however, been applied to the photovoltaic output characteristic in order to move I-V curve into the first quadrant of the I-V plane and to make it pass through the origin of this plane. This has done to compare the photovoltaic output characteristic with other two method. It is seen from the fig. 2.7 that curves differ slightly. For a given current I, the voltage associated with (photovoltaic output) curve 1 is

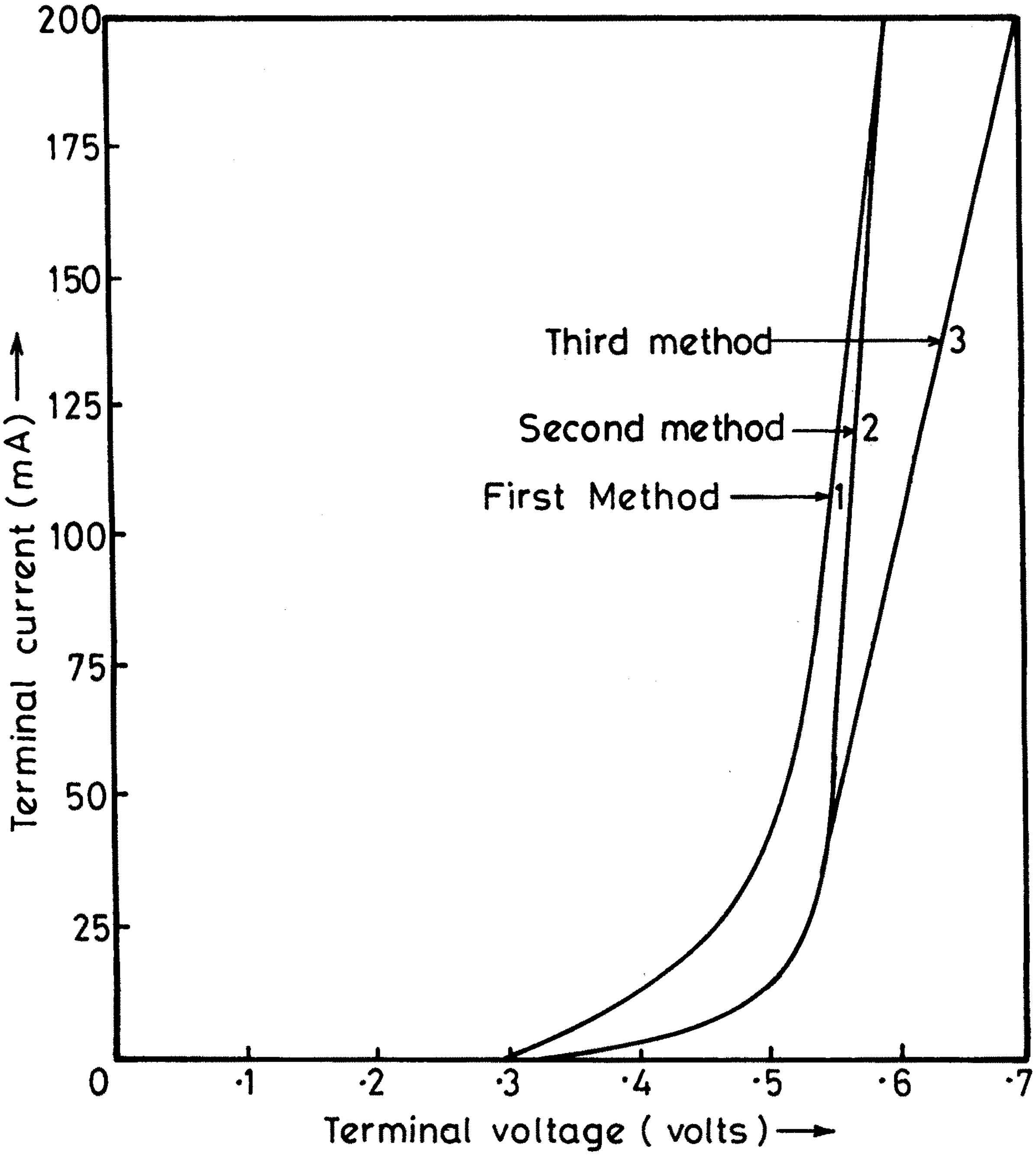


Fig. 2·7 The current voltage characteristics obtainable on the same solar cell by three different methods.

smaller than that of other two methods. This is understood with a fact that in the photovoltaic output characteristics, a current is generated internally in the cell giving rise to a voltage drop across p-n junction in the forward bias direction and causing current flow through this p-n junction and the series resistance.

2.4 Solar Cell Output Parameters :

In general, the photovoltaic output properties are studied with the help of experimental circuit diagram shown in fig.2.5. Under constant illumination the load resistance R_L is varied from zero to infinite ohms and corresponding I_L and V_L pairs are recorded. The pair of I_L and V_L at a load resistance R_L gives point in the I_L - V_L plane. These points when plotted in fourth quadrant of I_L - V_L plane, gives rise to a photovoltaic output characteristic as shown in fig. 2.8. The relationship between I_L and V_L is given by equ.(2.3). For an ideal solar cell, the series resistance R_s is minimum or zero, the junction ideality factor n, is one and the shunt resistance R_{sh} is infinite. Under these conditions the equation for photovoltaic output current is given by

$$I_L = I_o \left(\exp \left[\frac{e}{kT} V_L \right] - 1 \right) - I_{ph} \quad \ldots \quad (2.7)$$

In the short circuited condition, the load resistance R_L is zero, and hence V_L is zero. The current flowing the external circuit is the short circuit current denoted by

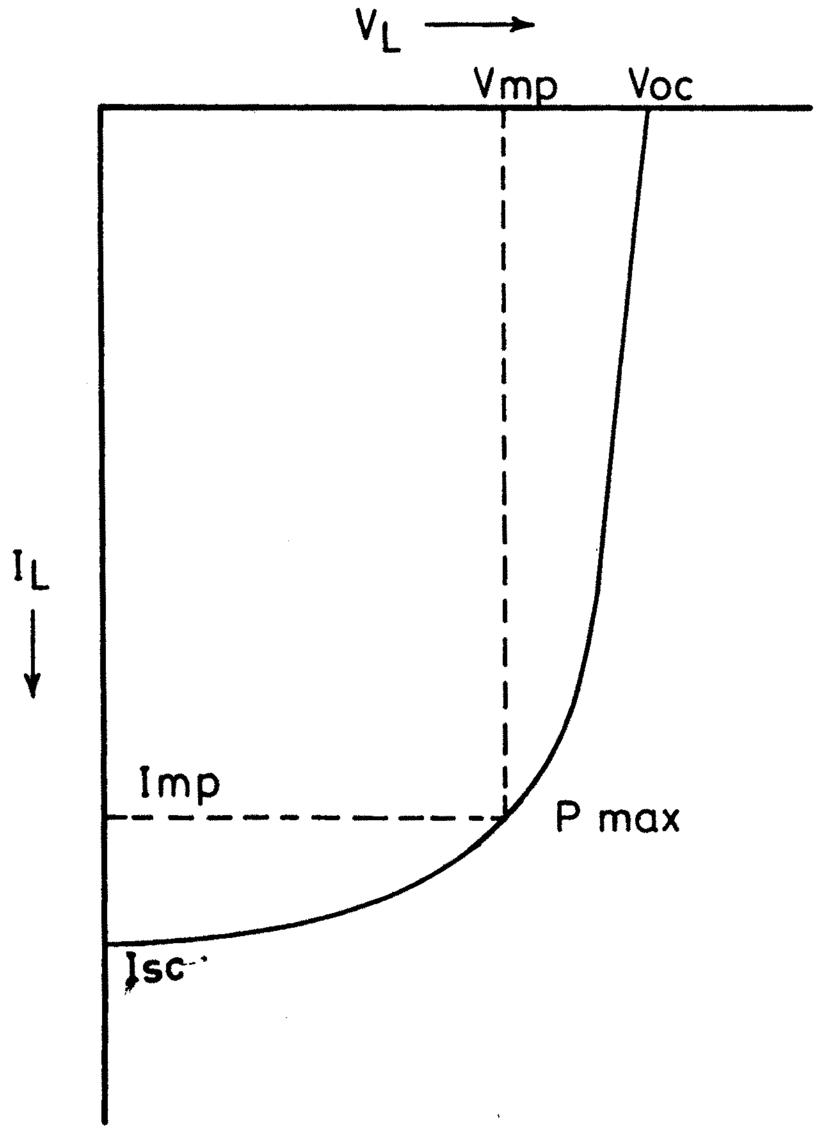


Fig. 2·8 Terminal properties of p–n junction solar cell when illuminated.

I_{sc} and from equation (2.7)

$$I_L = I_{sc} = - I_{ph} \qquad \ldots \qquad (2.8)$$

The short circuit current I_{sc} is related to the input radiation by :

$$I_{sc} = \int_0^{\infty} Q_c^{`} (1-R_n)(1-e^{-\alpha w})e \; nph \; (E)dE \quad \ldots \qquad (2.9)$$

where

$n_{ph}(E)$ = no. of photons per unit energy per second at energy E.

E = photon energy

W = thickness of absorbing semiconductor

α = absorption co-efficient.

R_n = Reflectance

Q_c = collection efficiency.

In the open circuit condition, the R_L is infinite, the current flowing through the external circuit is zero and V_L becomes maximum called the open circuit voltage V_{oc}. Under this condition one can write from equation (2.7)

$$V_{oc} = \frac{kT}{e} \ln \left(\frac{I_{sc}}{I_o} + 1 \right) \qquad \ldots \qquad (2.10)$$

At room temperature and with I_{sc} I_o

$$V_{oc} = 0.0575 \log \left(\frac{I_{sc}}{I_o} \right) \qquad \ldots \qquad (2.11)$$

From the equations (2.10) and (2.11) it is seen that V_{oc} is determined by the properties of semiconductor by the virtue of its dependence on I_o. Further it can be shown that the larger the band gap the larger the open circuit voltage.

The photovoltaic power output extracted from solar cell is dependent on the load resistance R_L . The variation of power P_L with the load resistance R_L is shown in fig.2.9.. It is seen that there is a unique value of R_L for a given solar cell where P_L is maximum and it is denoted by R_{LMP}. This parameter can be estimated as follows.

The power output across the R_L is given by

$$P_L = I_L^2 R_L \qquad \ldots \qquad (2.12)$$

Substituting the value of I_L from eq. 2.7 one gets

$$P_L = [I_o(\exp. \frac{eV_L}{kT} - 1) - I_{ph}]^2 R_L \qquad \ldots (2.13)$$

The condition for maximum power is

$$\left(\frac{d_{PL}}{d_{RL}} \right)_{R_{LMP}} = 0 \qquad \ldots \qquad (2.14)$$

Imposing this condition on equation (2.13) one gets

$$[I_o(\exp \frac{eV_{LMP}}{kT} - 1) - I_{ph}] = - 2R_L I_o \frac{e}{kT} e^{eV_{LMP}/kT} \frac{dVL}{dRL} \qquad \ldots \qquad (2.15)$$

Considering the standard relation $V_L = I_L.R_L$ one gets the expression

$$\frac{d_{VL}}{d_{RL}} = \frac{I_o (\exp. \frac{eV_{LMP}}{KT} - 1) - I_{pH}}{[1 - RL\, I_o \frac{e}{kT} e^{eV_{LMP}/kT}]} \qquad \ldots \qquad (2.16)$$

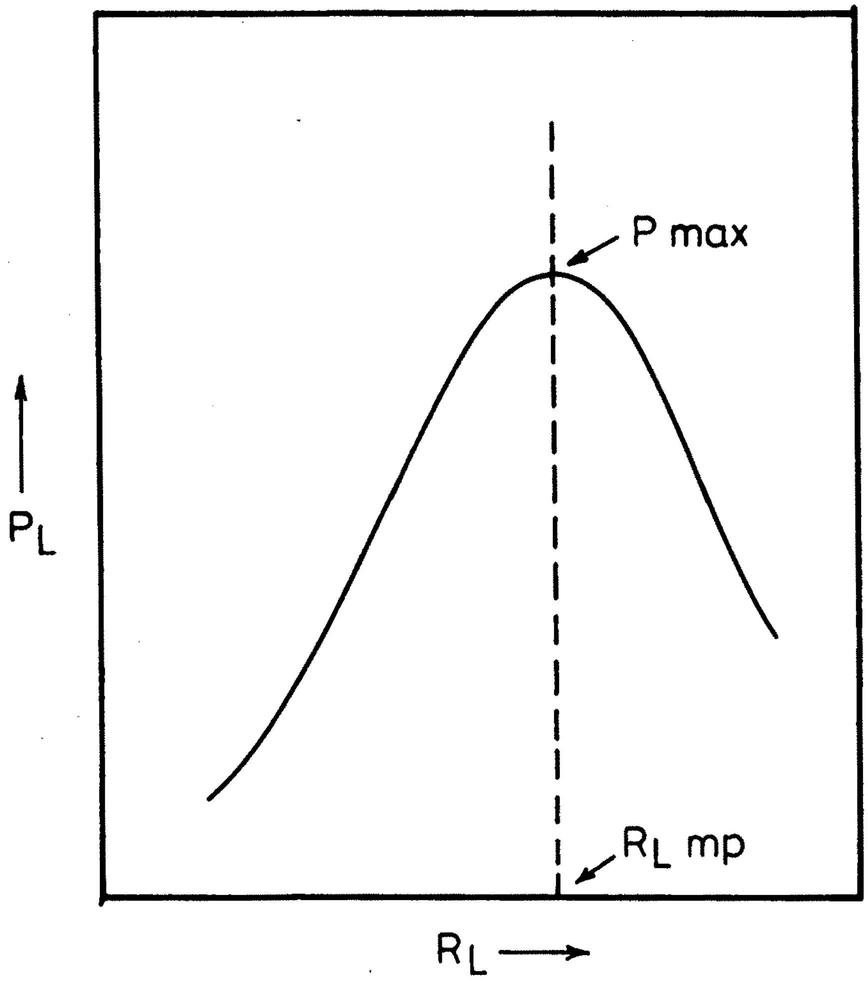


Fig. 2·9 Dependance of photovoltaic power output with load resistance R_L.

substituting equation (2.16) into equation (2.15) and rearranging the terms one gets

$$R_{LMP} = \frac{kT}{e} \frac{1}{I_o} \cdot \exp\left(\frac{-eV_{LMP}}{kT}\right) \qquad \ldots \qquad (2.17)$$

The maximum power transfer, from solar cell to the external electronic device, takes place only when the magnitude of R_{LMP} matches with the impedance of the external circuit.

From equation (2.17)

$$V_{LMP} = \frac{kT}{e} \ln\left(\frac{kT}{e} \cdot \frac{1}{I_o} \cdot \frac{1}{R_{LMP}}\right) \qquad \ldots \qquad (2.18)$$

The load current for maximum power output is

$$I_{LMP} = \frac{kT}{e} \frac{1}{R_{LMP}} \cdot \ln\left(\frac{kT}{e\, I_o R_{LMP}}\right) \qquad \ldots \qquad (2.19)$$

The maximum power output that can be extracted from solar cell is

$$P_{max} = I_{LMP} \cdot V_{LMP} \qquad \ldots \qquad (2.20)$$

and this is equal to the area of the rectangle indicated in fig. (2.8)

The fill factor (FF) of a solar cell is defined as

$$FF = \frac{I_{LMP} \cdot V_{LMP}}{I_{sc} \cdot V_{oc}} \qquad \ldots \qquad (2.21)$$

The energy conversion efficiency, η, is given by

$$\eta = \frac{I_{LMP} \cdot V_{LMP}}{P_{in}} = \frac{I_{sc} \cdot V_{oc} \cdot FF}{P_{in}} \quad \ldots \qquad (2.22)$$

where P_{in} is the total power in the light incident on the cell. In order to increase the efficiency, V_{LMP} value should be as large as possible for a given input. The values of V_{LMP} are large provided V_{oc} value is large. V_{oc} value is large provided the value of I_{sc} is as large as possible and I_o value as small as possible.

2.5 Effect of Resistance on the Performance of Solar Cells

Resistive components in solar cells result in power dissipation and hence impair the performance of the cells. There are two principle resistive components

i) series resistance (R_s) and ii) Shunt resistance (R_{sh})
The series resistance consist of mainly bulk resistance of the diode and the contact resistance. Taking into consideration the role of series resistance, the expression for the photocurrent is given by equation (2.3). Under open circuit condition $I_L = 0$, one gets the similar relation for V_{oc} from eq.(2.3) for an ideal solar cell. This shows that there is no effect of series resistance on the open circuit voltage, however, there is effect of series resistance on I_{sc}. Under short circuit condition $I_L = I_{sc}$ and $V_L = 0$ eq.(2.3) modifies to

$$I_{sc} = I_o \left(\exp\left[\frac{-e\, I_{sc}.R_s}{nkT}\right] - 1\right) - I_{ph} \quad \ldots \qquad (2.23)$$

Theoretical I-V characteristics for various converters with different values of R_s are shown in fig. 2.10. It may be seen that though the V_{oc} does not change with R_s, the magnitude of I_{sc} and nature of the photovoltaic output curve change predominantly.

2.6 Measurement of Series Resistance

The series resistance of a solar cell can be measured by illuminated curve method. Though this method was first suggested by Swanon in 1960, it was Wolf and Rauschenbach, who have studied it systematically. This method consists of the measurements of photovoltaic output characteristics at two different light intensities, the magnitudes of which need not have to be known. The two characteristics are to be shifted against each other by the amount ΔI_L and ΔV in the current and voltage axes respectively such that there is perfect overlapping of the curves. The displacement parallel to voltage axis equals $\Delta V = \Delta I_L.R_s$. This procedure is illustrated in fig. 2.11. From the values of ΔI_L and ΔV one obtains the value of R_s.

An alternative to the above procedure has been suggested by Wolf and Rauschenbach. An illustration of the procedure is given in fig. 2.12. In brief, following are the steps :

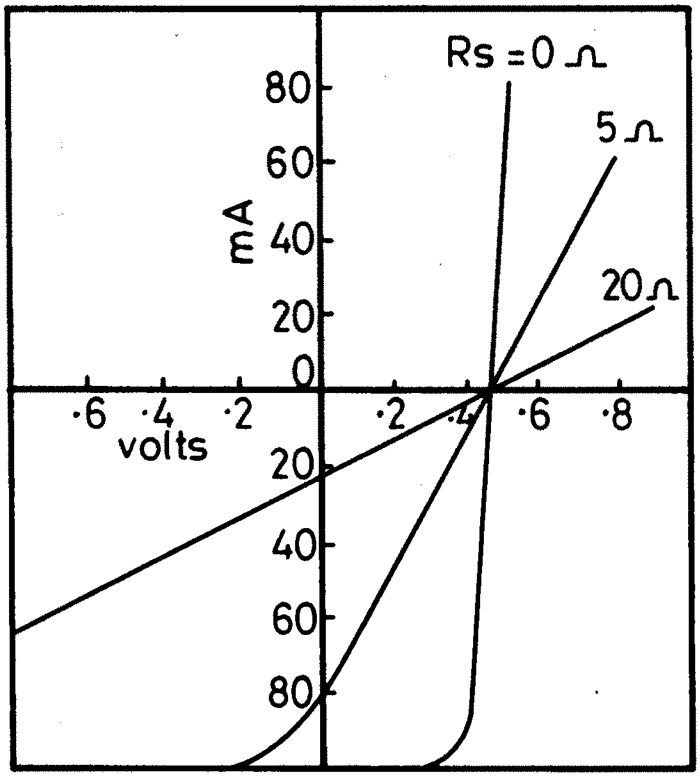


Fig. 2·10 Theoretical I-V characteristic for three solar cells with different Rs.

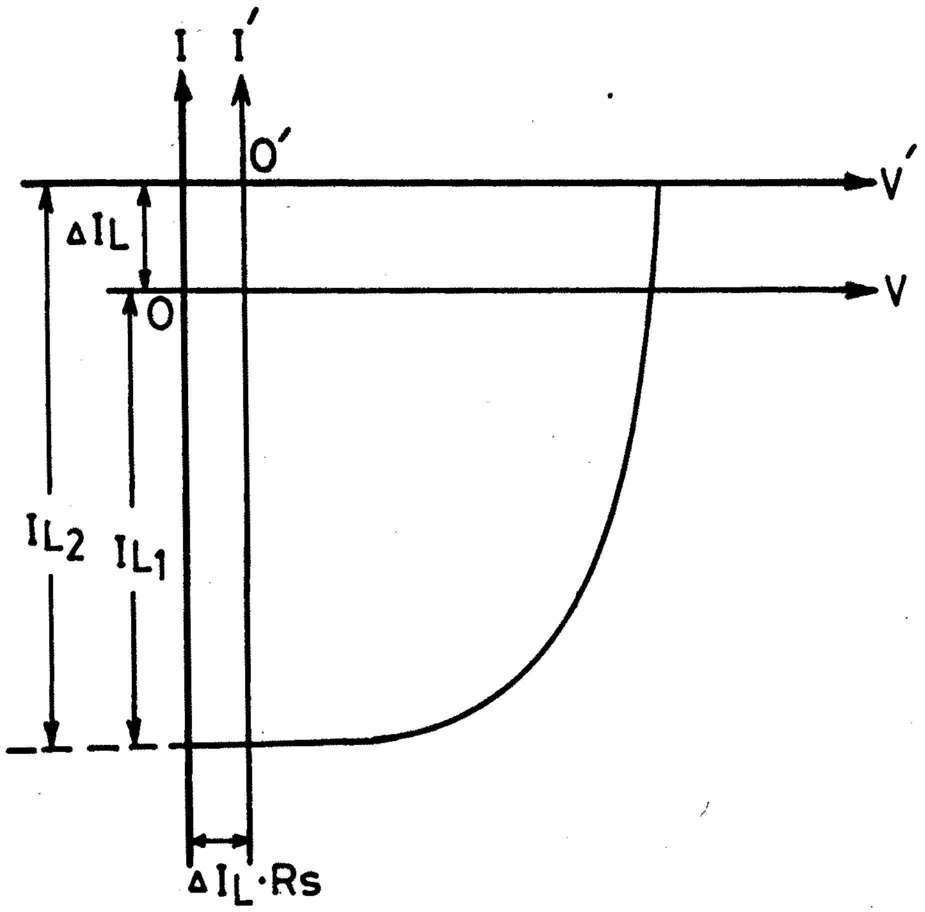


Fig. 2·11 Illustration of procedure to obtain Rs.

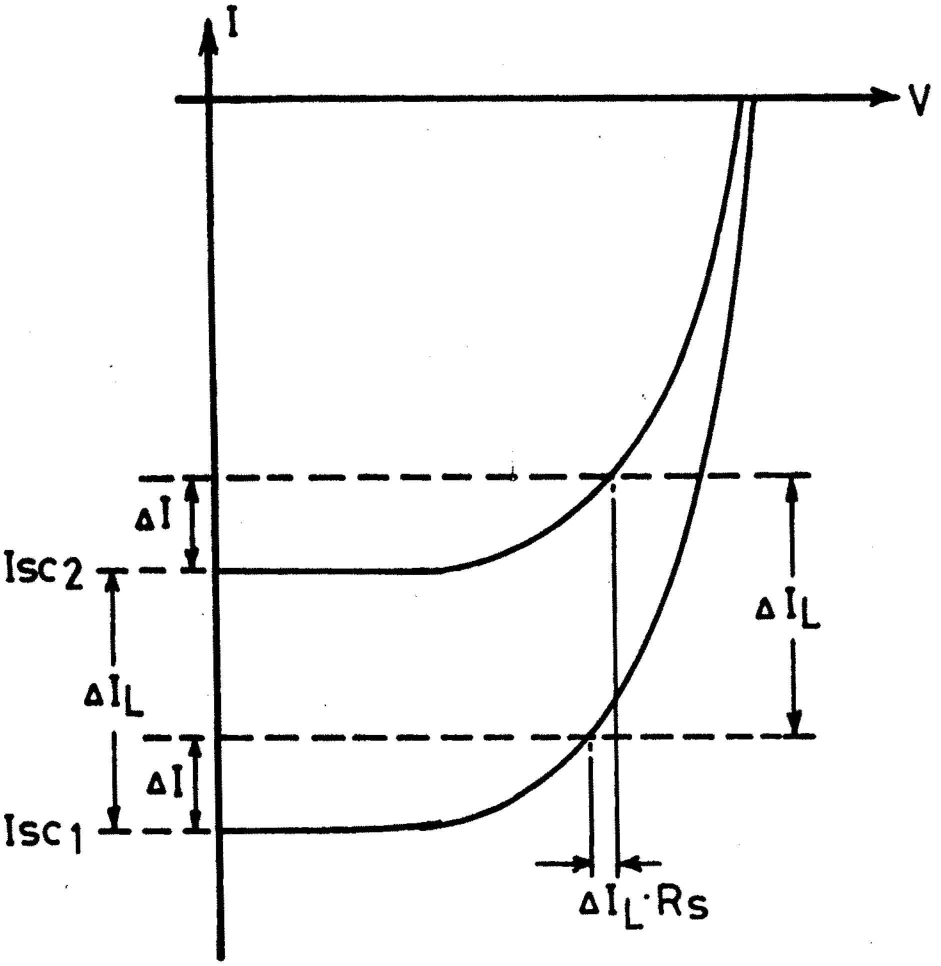


Fig. 2·12 Illustration of an alternative procedure to find Rs.

Record the photovoltaic output characteristics at two different light intensities. Choose an arbitrary interval ΔI, from I_{sc1} of the first characteristics, use the same ΔI value from I_{sc2} for finding a second corresponding point on the second characteristic. Find ΔI_L and $\Delta V(= \Delta I_L . R_s)$. Generally it is convenient to choose ΔI as to obtain a point in or near the knee of I-V curve.

2.7 Basically required Properties of Materials for use in Solar Cell

i) $h\nu > E_g$ i.e. the energy of the incident light should be greater than the band gap of the semiconductor. The optimum band gap lies between 1.2 to 1.8 eV.

ii) The absorption coefficient, α, of a semiconductor must possess a large value.

iii) The reflection and the transmission coefficients of the semiconductor must be small.

iv) The thickness of the bulk of the semiconductor must be optimum.

v) Charge carriers of the material should have high mobilities and lifetime.

vi) Cost of material, manufacturing process and efficiency should be acceptable.

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