

THEORETICAL AND EXPERIMENTAL STUDY
OF THE PHOTOVOLTAIC EFFECT
IN THIN FILMS

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DEDICATION

This work is totally dedicated to my beloved wife,

Tsadkan Zebello

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ABSTRACT

In the present study the theory of photovoltaic energy conversion is presented. Basic factors affecting conversion capability of photovoltaic devices are discussed. General formula of the minority carrier distribution and current density across p-n junctions are revised and further developed to arrive at the over all collection efficiency expression which is valid for any thin film photovoltaic cells. Focus is put on the main solar cell parameters like conversion efficiency and spectral response.

To the end some experimental works on a single crystal solar cell (FD-K) are made. Emphasis is put on establishing circuits capable of measuring various solar cell parameters ranging from Si-single crystal cell of low efficiency. The results of the measurement are presented in the form of tables and graphs. Conclusions are also made on the results obtained.

INTRODUCTION

The problem of energy has remained to be the fundamental question for development in the history of mankind. The truth is that this question has stayed valid till this era and will remain the same for ever regardless of the socio-economic formation in which any nation is found to be.

As fundamental the problem of energy has been to every society, energy resources are not either distributed fairly among every nation or their utilization may require far beyond the nation's income. Even those who have got hold of the relatively bulky resources and are capable of utilizing their conventional energy resources, a danger awaits them in their forefront, in the rate of depletion and the problem of pollution associated with the present conventional fossil fuel resources are of paramount concern.

In view of the anticipated future energy crisis and pollution problems much attention has been focused on solar energy as a new resource alternative to the conventional fossil fuels. This is because solar energy is extremely abundant, limitless, stable and is free from the pollution problems associated with the conventional resources. Hence, many research works are being conducted in many countries to realize the possible exploitation of this abundant energy resource efficiently. As a reply to this urge, solar-photo-voltaic converters (so called) have been evolved

The most important application for solar cells since the past has been in the space programme. Many satellites orbiting around the earth are powered to a very large degree by solar cells. The sophisticated weather forecasting, communication, military and other scientific capabilities the world has today would have not been realized without these cells.

Solar cells are more advantageous than any other power generators known hitherto in their ability to provide nearly permanent, uninterrupted power at no operating cost with only heat as a waste product, and then conversion of light directly into electricity with no need of some other intermediate form of energy. They also have a high power to weight ratio compared to other devices. Their chief disadvantages lie in the low power per unit area of sunlight which necessitates a construction of large area arrays, in their relatively low efficiency, and in the degradation that takes place in hostile high energy particle environments.

As useful as solar cells have been in the space programme their potential importance for large scale power generation to meet earth's energy needs is even greater. A few years ago, very few people would have seriously proposed solar energy as a major power source. Because fossil-fuel burning, steam-power generation plants were cheap and fuel supplies seemed inexhaustible. Today, however, the rising price of fuel, and the realization that oil and gas supplies can only last a

relatively few decades, and the freedom of solar energy from pollution, have all led to closer looks at solar energy as an alternative to present day fossil-fuel systems.

Owing to the above importance of solar energy, many researchers have attempted to devise ways of realizing and harnessing this energy to man's needs. A short account of its historical development would help us see the evolutionary process of solar energy utilization in the world.

It has been almost a century and a half since Becquerel in 1839 first discovered that a photovoltage was developed when light was directed on to one of the electrodes in an electrochemical solution. This effect was observed to occur in a solid (semiconductor) forty years later by Adams and Day [2]. A number of other solid-state workers including Lange [3], Grondahl [4] and Schottky [5] did pioneering work on selenium and cuprous oxide photovoltaic cells. Beginning from 1954, work on utilization of the photovoltaic effect appeared in the literature. In the same year an RCA group [6] demonstrated the conversion of radioactive radiation into electrical energy using a silicon p-n junction photovoltaic cell. This was followed by Chapin, Fuller and Pearson [7] who were able to report a 6% conversion efficiency. In that same year Reynolds, Leies, Antes and Murrberger [8] reported about 6% solar-photovoltaic conversion efficiency using cadmium sulphide p-n junction.

Up to the present time tremendous efforts have been made by many scholars involved in the field to improve solar-photovoltaic conversion efficiencies. Single crystal solar cells for which efficiency measurements in the range of 5% to 18%, and thin film polycrystalline solar cells of efficiencies between 5% to 9% were reported upto the year 1978 [9].

The efficiencies reported considerably depend on the methods used during the processing of the devices and also on the types of the materials used. For example, high efficiency electroplated heterojunction thin film solar cell (CdS/CdTe) was reported by Eulent M. Pasol in 1984 [10] while in the same year CdS/CdTe thin film solar cell fabricated by the close-spaced-sublimation (CCS) process had higher efficiency (>10%) [11].

The over-all efficiency comparisons between single crystal solar cells and thin film polycrystalline solar cells places the former in the superior position. However, there is no fundamental barrier to the achievement of higher efficiencies in thin film cells and, indeed, their limiting efficiency should in principle be comparable to the efficiencies achieved and achievable in single crystal cells.

From the economic point of view the production of single crystal cells of the required purity involves an inherently expensive process while thin film solar cells could be produced

at a relatively lower cost technology. Thus, the real future of photovoltaic energy conversion appears to be closely connected with the possibility of producing thin film photovoltaic cells.

The general objective of the present thesis work focuses on studying the main characteristics of thin film photovoltaic generators and the factors which affect their performance. To this end, the paper is organized in such a way that the first chapter entails the general theory of photovoltaic effect in thin film solar cells. In the second chapter, the various factors which affect photovoltaic solar energy conversion performance are discussed. Analytical treatment of the transport problem of excess minority carriers in single crystal p-n junction is revised and utilized for further developing the over-all collection efficiency (spectral response) expression in this chapter. The next two chapters summarize the main functions and characteristics of electrical connections and environmental interfaces of a generalized thin film solar cells and the design options in the present time solar cell production. The final chapter embodies the experimental measurements carried on a given sample solar cell (Si) which was in our disposal. Its efficiency, spectral response, current-voltage, and capacitance-voltage measurements are given, and calculations of the barrier-height, and donor density in the dark and under illumination are made.

The fabrication of a thin layer solar cell by electroplating method according to B.M. Basol [10] which was originally planned could not be realized, because of lack of certain chemicals. An attempt to produce a photoelectrochemical cell according to Ki Hyun Yoon [12] was not also successful because Titanium sputtering was not available. The obstacles mentioned above led us to perform a thorough theoretical and experimental study of the solar cell.

CHAPTER 1

THE THEORY OF PHOTOVOLTAIC EFFECT (PVE)

IN THIN FILMS

PVE is the generation of an electromotive force (EMF) by the absorption of light (or ionizing radiation) in an inhomogeneous solid. It is distinguished from localized heating which can produce an EMF via thermoelectric effects or the Dember effect which results from non-uniform illumination in a homogeneous solid.

1.1. Necessary conditions for PVE occurrence.

In order for a PVE to occur in a system, the following criteria must be fulfilled.

Light must be absorbed in the semiconductor and mobile charge carriers must be generated as a result of the absorption; the light generated excess carriers must be separated by a built-in electrostatic field (built-in potential barrier); and the lifetime of the excess carriers must be long enough to allow them to travel from the places where they are generated to the charge separation site.

1.1.1. Light absorption.

Absorption takes place when photons are incident on the solar cell provided that their energy is greater than the band gap.

The ability of a material to absorb light of a given wavelength is measured quantitatively by the absorption coefficient α , measured in units of reciprocal distance. Light at the surface of solar cells falls off in intensity, a factor of $1/e$ for each $1/\alpha$ distance into the material. As a general rule, the wider the band gap, the smaller the value of α for a given wavelength. The absorption coefficient also depends on the densities of states in the conduction and valence bands [13] and the directness and indirectness of the band gaps.

1.1.2. Charge Separation.

As soon as absorption takes place electrons are raised in energy from the valence band to the conduction band, creating electron-hole pairs. These light generated carriers must then be separated by a built-in electrostatic field so that they can diffuse to the edges of the space-charge region before they recombine. As a result of this field they are swept across the junction giving rise to a photocurrent, photovoltage and power to a desired load.

This barrier is merely a result of electronic inhomogeneity in the system; and is usually called the electronic junction. It is the site of the potential barrier which is necessary for a photovoltaic device.

The junction can be 1) a p-n junction (homojunction) ma

of conductivity; 2) a heterojunction composed of two different semiconductors; 3) a Schottky barrier which is a metal semiconductor (MS) junction or 4) a metal-insulator-semiconductor (MIS) junction.

1.1.3. Carrier lifetime.

The excess carriers generated as a result of the absorption of ionizing radiation must remain free long enough to travel from the point of generation to the charge separation site.

Once an electron has been optically excited to the conduction band leaving a hole in the valence band, it may either recombine with a hole or migrate to the edge of the semiconductor and be collected for useful work. The collection of photogenerated carriers across the p-n junction is in competition with the loss of these carriers by bulk and surface recombination before they can be collected. Bulk recombination can occur by direct mutual annihilation of a free electron and a free hole or by annihilation through an intermediate recombination center.

The intermediate recombination is usually the dominant mechanism. If there are N_x recombination centers located at an energy level E_x and having capture cross-sections σ_n , σ_p for an electron when empty and for a hole when filled, the

the hole-life time on the n-side of the junction can be described by [13].

$$\tau_p = \frac{1}{\sigma_p v_{th} N_r} \left[\left(1 + \frac{N_c}{n_{no}} e^{-\left(\frac{E_c - E_r}{KT}\right)} \right) + \left(\frac{\sigma_p}{\sigma_n} \right) \left(\frac{N_v}{n_{no}} \right) e^{-\left(\frac{E_r - E_v}{KT}\right)} \right]$$

where N_c, N_v are the number of conduction and valence electrons, n_{no} is the free electron concentration on the n-type side and is essentially equal to the doping level, v_{th} is the thermal velocity, K is the Boltzmann constant, and E_c and E_v are the conduction and valence band edges, respectively. An analogous equation can be obtained for the electron life-time in p-type material. The actual life times are determined by a multiplicity of such recombination centres at a number of energy levels, qualitatively, this equation indicates that the life time will decrease with increasing doping level and saturates at a value equal to

$$\tau_{po} = (\sigma_p v_{th} N_r)^{-1} \tag{1.2}$$

In addition to a recombination in the bulk, a loss of photogenerated minority carriers also takes place at the surface of the material due to the presence of surface states which arise from dangling bonds, chemical residues, metal precipitates, native oxides, and the like [13].

The rate at which carriers are lost at a surface is described by the surface recombination velocity S which is related with the minority-carrier current density towards the surface by

$$J_{\text{surface}} = q S_p (p_n - p_{no}) \quad (1.3)$$

for holes in an n-type material and

$$J_{\text{surface}} = q S_n (n_p - n_{po}) \quad (1.4)$$

for electrons in a p-type material. $p_n - p_{no}$, $n_p - n_{po}$ are the excess carriers in the n and p type material respectively.

If the surface diffusion length $L_{S_{p,n}}$ for holes and electron is known the hole and electron life-times and the corresponding surface recombination velocities $S_{p,n}$ could be related as

$$\tau_{p,n} = \frac{L_{S_{p,n}}}{S_{p,n}} \quad (1.5)$$

For specimens that have a high concentration of impurities the scattering is frequent, the mean free paths are short, and the mobilities are low. Crystals that are heavily doped usually have low mobilities in the extrinsic temperature range. Imperfections in the crystal arise due to dopants, vacancies, dislocations in the bulk. These together with imperfections on the surface are recombination centers and thus decrease the diffusion length and life-times of the electron-hole carriers.

As decisive as these imperfections are to the cause of recombination effects in single crystals, their effects are highly pronounced in thin films. Because, thin films usually contain far more bulk defects in single crystals made from the same semiconductor, and because recombination at the grain boundaries can severely limit solar cell performance.

1.2. The effects of grain boundaries on the carrier life time in polycrystalline thin films

A thorough analysis of grain boundary effects on both the photocurrent and dark current in thin film solar cells has never been carried out as far as our knowledge of the problem is concerned. A complete analysis of this problem entails a three dimensional solution to the diffusion equation with edge boundary conditions. Partial solution for the simpler case of uniform generation of minority carriers throughout a volume rectangular filament has been achieved by [14] where he used his analysis to define a "filament life-time" made up partly of the bulk life time in the filament and partly of surface recombination life time in the filament. When the filament dimensions are small and the surface recombination velocities are high, the recombination in the filament is dominated by surface terms and the "filament life time" is much smaller than the bulk life time. Similar considerations apply to polycrystalline film, which can be thought of as many filaments connected in parallel and sometimes in series.

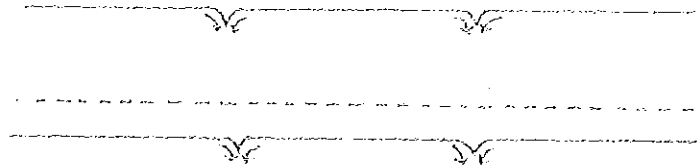


Fig.1.1.1. Energy profile in the vicinity of grain boundaries.

If Figure 1.1, an energy profile at and around grain boundaries is shown. Theoretically, it appears that grain boundaries act as minority carrier sinks (surface of high recombination velocity) and majority carrier barriers, they reduce the photocurrent, increase the dark current, decrease the shunt resistance and increase the series resistance.

One possible combination of grain boundaries is when a random orientation of the grains prevail as shown in Fig.

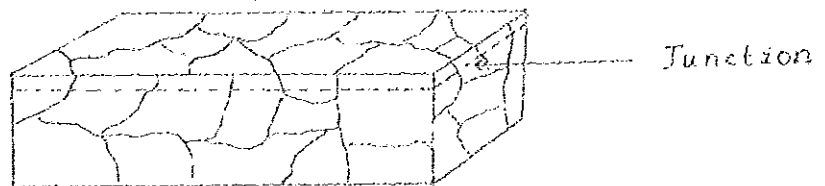


Fig.1.1.2. Random orientation of grains.

In such a situation only the top most grain or two grains will be able to contribute to the output; the grains which are below are effectively isolated from the junction by the

boundaries above them. This gives the series combination grain boundaries in which the effective carrier life time in the film will be very low and the device will behave very poorly.

Another possible orientation of the grains is a fibrous epitaxial type as shown in figure 1.3.

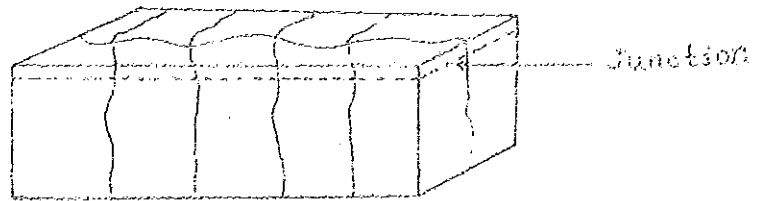


Fig.1.3. Fibrous epitaxial orientation of grains

In such thin film structures, minority carriers within each filament can cross the junction boundary and the whole layer thickness can contribute to the output. In such a situation the overall solar cell can be thought of as a parallel combination of filamentary solar cells, each of which act in a normal manner except that minority carrier recombination can take place on the sides of the filaments as well as at the front surface and back contact.

A schematic representation of individual grains in polycrystalline thin film solar cells is shown in figure where the surfaces of the grain are characterized by surface recombination velocities: S_s for the surface on which the light is incident; S_{gb} for the surface of the grain boundary

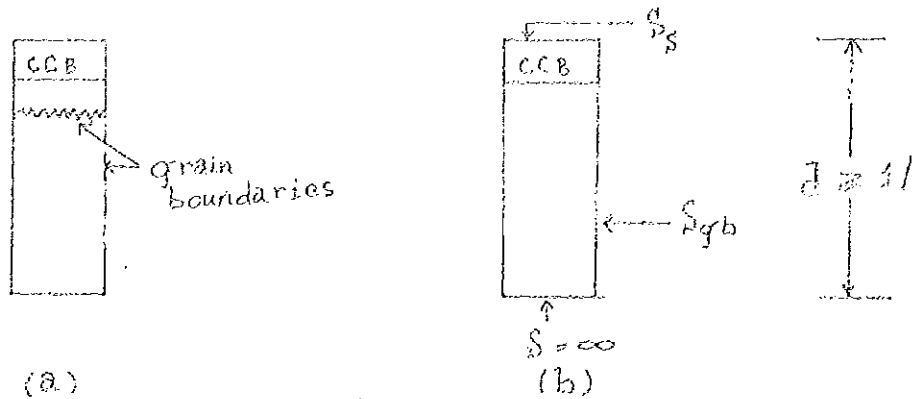


Fig.1.4. Schematic representation of individual grain of the type which could be encountered in polycrystalline solar cells.

The presence of a grain boundary parallel to the major surface area of a grain as shown in figure 1.4a reduces the grain dimensions and thus carriers generated by photons absorbed in the region below this grain boundary can not migrate to the charge collection barrier (CCB).

As regards the vertical grain boundaries and how they affect recombination, Shockley treated the transport problem of minority carriers injected into a filament of rectangular cross-sections [14]. He showed that the effective diffusion length of minority carriers traversing the filament was equal to the bulk diffusion length of the filament provided that the filament dimensions were equal to or greater than the bulk diffusion length L_B , even if the recombination velocity at the grain boundaries, S_{gb} , is infinity. This conclusion has important consequences with respect to the

thinner films of direct gap semiconductors are needed to absorb most of the light absorbable by the semiconductor and this thickness is of the order of several microns. The value of L_E needed to collect most of these photons is of the same magnitude as the effective absorption depth X_{eff} . Since the grain dimensions need only be approximately equal to L_E , this means that grain sizes of several microns are sufficient to make thin film solar cells from direct gap semiconductor whose recombination properties should be comparable to those of large single crystal cells from the same semiconductors.

In the case of an indirect gap semiconductors like Si, etc. however, the effective absorption depth is of the order of a hundred microns and required grain dimensions are of the same order.

This simple examination of the problems associated with grain boundaries and their recombination effect illustrates the advantage of direct gap semiconductors for use in thin film solar cells.

Surface recombination losses could be minimized by increasing the grain dimensions. Other approaches involved application of appropriate chemicals which alter the defect structure at the surface.

A phenomenally successful approach is the one suggested by J.J. Loferski [9]. It involves the incorporation of minority carrier mirrors (MCM) i.e. potential barriers which drive minority carriers away from the surface towards the charge collection barrier.

CHAPTER 2

THE FACTORS AFFECTING PHOTOVOLTAIC SOLAR ENERGY
CONVERSION PERFORMANCE

In this chapter the main factors which limit the photovoltaic energy converter performance will be elaborated, and possibilities for their improvement will be discussed. Throughout the discussion the five-layered generalized thin film solar cell will be borne in mind.

The generalized thin-film solar cell can be thought consist of 1) an encapsulant antireflecting coating, 2) a transparent ohmic contact, 3) an absorber-generator semiconductor layer, 4) a collector-converter semiconductor layer, and 5) an opaque ohmic contact as schematically shown in Figure 2.1.

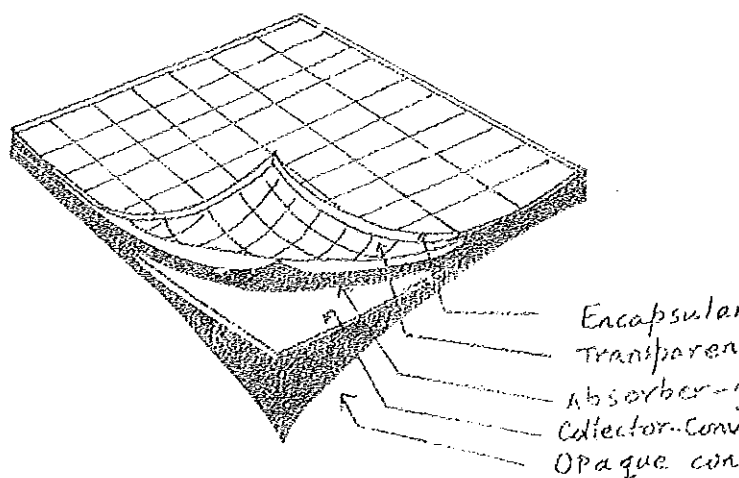


Fig.2.1. A five layered generalized thin film solar Cell.

2.1. Semiconductor Layers

The essential features of any solar cell are an

absorber-generator material in which mobile carriers are generated by the absorption of light, and a built-in potential region which allows the generated carriers to be collected from the region in which they were generated and converted to majority carriers. This collector-converter prevents the back flow of carriers.

The absorber-generator region determines the magnitude of the current that is generated and the height of the potential barrier determines the voltage the cell can produce. In some structures the absorber-generator can be in the region where the transition to the voltage differential occurs, the space charge region.

The product of voltage and current creates the power which, when integrated with time, represents energy of the source which is able to perform work.

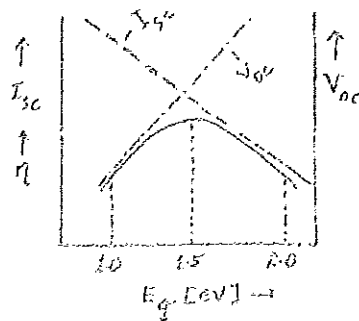
2.1.1. Selection of optimum energy gap materials.

The photon absorber-generator region is characterized by the following parameters: the energy gap, the absorption coefficient and the minority carrier diffusion length.

The energy gap determines the maximum efficiency of the cell that can be achieved utilizing a single absorber-generator. Incident photons in the solar spectrum with an energy equal to or greater than the energy gap excite free carriers (electron-hole pairs) and determine the maximum obtainable

current that can be generated. The maximum voltage is also determined by the energy gap of the absorber-generator and the characteristics of the junction formed with the collector-converter.

Figure 2.2 below shows the dependence of conversion efficiency on the energy gap as given by [9]. It gives a guidance as to the wide choice of materials for an absorber-generator. On the same figure, an approximate dependence of the short-circuit current and the open-circuit voltage of the energy gap is shown.



$$\eta = I_{sc} V_{oc} \times \text{Fill Factor}$$

$$I = \int_{E_g}^{\infty} n_{ph}(h\nu) Q(h\nu)$$

$$V_{oc} = \frac{AkT}{q} \ln \left(\frac{I_{sc}}{I_0} \right)$$

$$I_0 \propto k \exp \left(-\frac{E_g}{kT} \right)$$

Fig.2.2. The approximate dependence of I_{sc} , V_{oc} and η on energy gap of the semiconductor comprising the solar cell.

2.1.2 Selection of Optimum Thickness

It is necessary to define the limits of thickness that qualify a semiconducting material as a thin film solar cell. For the absorption capability of materials, among many other possible factors, depends upon the thickness of the absorber-generator layer.

Consider a beam of light having wavelength λ , normal incident on a semiconductor having an absorption constant α for this particular wavelength. Then the flux of photons $N_{ph}(x)$ remaining in the beam after it traverses a thickness of semiconductor is given by

$$N_{ph}(x) = N_{ph}(0) e^{-\alpha(x)} \quad (2.1)$$

where $N_{ph}(0)$ is the normally incident photon flux.

The wavelength dependence $\alpha(\lambda)$ of two hypothetical semiconductors having the same energy gap E_G are shown in figure 2.3. One of them is a direct gap, the other an indirect gap semiconductor. Suppose photons having energy $E_G + \Delta E$ incident normally on each of these semiconductors. If the respective thickness of each of them is x_d and x_i , then according to equation (2.1)

$$\frac{x_i}{x_d} = \frac{\alpha^{(d)}}{\alpha^{(i)}} \quad (2.2)$$

where $\alpha^{(d)}$ and $\alpha^{(i)}$ are the absorption constants for photons of energy $E_G + \Delta E$ in the direct and indirect gap material respectively.

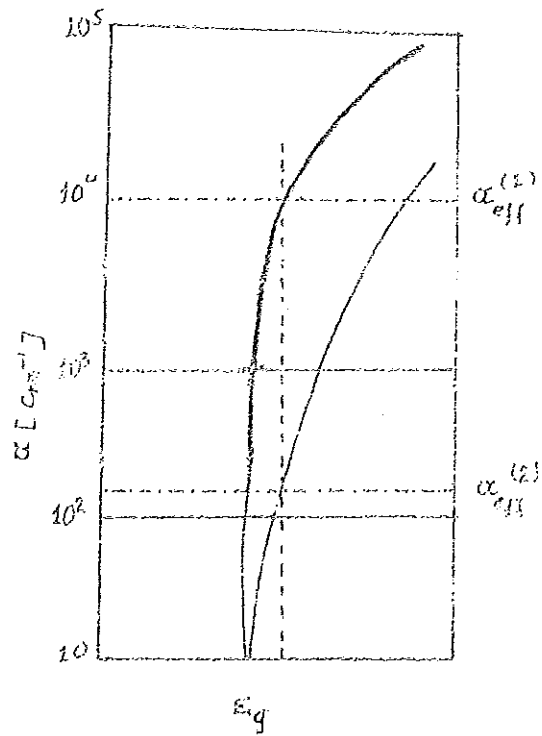


Fig.2.3. Hypothetical absorption characteristics (α versus $h\nu$) for two semiconductors (1-direct, 2-indirect) having the same energy gap.

For illustration purposes, consider the direct gap semiconductor GaAs ($E_G \approx 1.35$ eV) and the indirect gap semiconductor Si ($E_G \approx 1.1$ eV). For $E = 0.2 E_G$, X_{eff} is about $7 \mu\text{m}$ ($14 \mu\text{m}$ optical path length) for GaAs and about $500 \mu\text{m}$ ($1000 \mu\text{m}$ optical path length) for Si. The power output of a photovoltaic cell is proportional to the power absorbed in the cell from the incident light. Approximately the same fraction of photons having an energy in excess of their respective band gaps is absorbed by $7 \mu\text{m}$ of GaAs and $50 \mu\text{m}$ of Si. Therefore, GaAs is more suited for thin film solar cells than Si; i.e., direct gap semiconductors have distinct advantage over indirect gap semiconductors as the basis of thin film photovoltaic solar cells.

In figure 2.4 below absorption constants for the materials presently under study are superimposed on the photon flux of the solar spectrum as given by [15]. Convoluting the spectral density with absorption coefficient, one finds that the only material with energy gap between 1.0 and 1.7 eV which cannot absorb 90% of the photons, say, in a $5 \mu\text{m}$ thick film is crystalline silicon. Crystalline silicon will absorb 70% of the photons in a $10 \mu\text{m}$ thickness and 90% of the photons in a $100 \mu\text{m}$ thickness.

In contrast to silicon, many of the materials will absorb 90% of the available sunlight in thickness less than $1 \mu\text{m}$, e.g., Copper Sulphide will absorb 90% of this sunlight

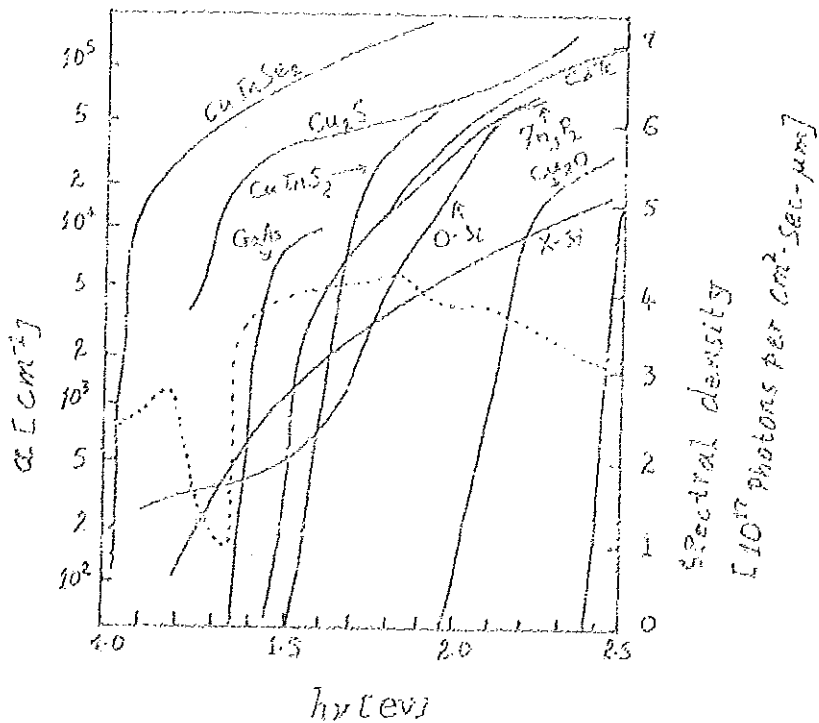


Fig.2.4. Thin film solar cell materials absorption coefficient versus photon energy.

Therefore, materials with the ability to absorb light in thinner layers are best candidates for thin film photovoltaic energy converters, for they given the prime answer to economic concerns.

2.2. The transport problem of the generated minority carrier

Most of the electron-hole pairs created by photon absorption are not generated within the space-charge region of the p-n junction. Therefore, on the average only those electron-hole pairs which are within a diffusion length from the junction can be collected while the majority of pairs generated in far away distances from the junction will suffer recombination, thus causing the collection efficiency to fall below 100%.

The collection process is determined by material constants, the location of the pair generated by the absorption mechanism, the diffusion of the pair generated which is determined by carrier mobility, and recombination which is determined by minority carrier life time.

In this section a general analytical evaluation of the collection process which was carried by [16] will be revised in detail, and will be developed to obtain the spectral response expressions.

The assumptions made are a uniform n-p or p-n junction with constant mobility, life time and doping.

2.2.1. Evaluation of minority carrier distribution

A one dimensional model is considered throughout. The number of photons absorbed per unit time in a unit area of a layer

thickness dx at a distance x below the surface is given by Lambert's law of absorption as

$$g(x)dx = \alpha N e^{-\alpha x} dx \quad (2.3)$$

where this gives the number of electron-hole pairs generated

The continuity equation for excess holes above the equilibrium density in an n-type material is given by

$$\frac{\partial p}{\partial t} = \frac{-p}{\tau} + D_p \frac{\partial^2 p}{\partial x^2} + \alpha N e^{-\alpha x} \quad (2.4)$$

where $\frac{\partial p}{\partial t}$ is the rate of change of minority carriers (holes) in the n-type material, $\frac{-p}{\tau}$ is the recombination rate of minority carriers in excess of the equilibrium density P_n , $D_p \frac{\partial^2 p}{\partial x^2}$ is the diffusion rate into (out of) the layer under consideration.

For solar energy conversion, the steady state case is of interest. Thus, one obtains from (2.4)

$$D_p \frac{d^2 p}{dx^2} - \frac{p}{\tau} + \alpha N e^{-\alpha x} = 0 \quad (2.5)$$

Using Einstein's relation between diffusion length L , diffusion constant D , and minority carrier life time τ i.e.

$$L = (D\tau)^{1/2} \quad (2.6)$$

in equation (2.5), the following expression is obtained.

$$\frac{d^2 p}{dx^2} - \frac{1}{L^2} p + \frac{\alpha N}{D} e^{-\alpha x} = 0 \quad (2.7)$$

Solution of this inhomogeneous differential equation is evaluated as follows. First we find the solution for the homogenous part:

$$\frac{d^2 p}{dx^2} - \frac{1}{L_p^2} p = 0 \quad (2.8)$$

which has a complementary solution p_c given by

$$p_c = p_1 e^{\frac{x}{L_p}} + p_2 e^{-\frac{x}{L_p}} \quad (2.9)$$

The particular solution p_p which will satisfy equation is

$$p_p = A e^{-\alpha x} \quad (2.10)$$

where A is determined by substituting equation (2.10) and its spatial second-derivative into equation (2.7) and p_p is found to be

$$p_p = - \frac{N}{\alpha^2 D_p (1 - \frac{1}{\alpha^2 L_p^2})} e^{-\alpha x} \quad (2.11)$$

Thus, the general solution to the differential equation given in (2.7) is

$$p = p_c + p_p \quad (2.12)$$

i.e.

$$p = p_1 e^{\frac{1}{L_p} x} + p_2 e^{-\frac{1}{L_p} x} - \frac{N N e^{-\alpha x}}{\alpha D_p (1 - 1/\alpha^2 L_p^2)}$$

For the minority carriers (electrons) in p-type material an equivalent expression exists

$$n = n_1 e^{\frac{1}{L_n} x} + n_2 e^{-\frac{1}{L_n} x} - \frac{N e^{-\alpha x}}{\alpha D_n (1 - 1/\alpha^2 L_n^2)}$$

The constants p_1 , p_2 , n_1 , n_2 are determined from the following set of boundary conditions:

1) At $x = 0$, surface recombination takes place which is given by

$$D_n \left(\frac{dn}{dx} \right)_{x=0} = S_n n(0)$$

2) At $x = x_j$ is a p-n junction kept in the zero-bias condition leading to short-circuit current so that a perfect sink for minority carriers exist. This is expressed as

$$n(x_j) = p(x_j) = 0$$

3) Surface recombination also takes place at the back surface that is at $x = d$. This is expressed as

$$D_p \left(\frac{dp}{dx} \right)_{x=d} = S_p p(d)$$

Frequently ohmic contacts are applied to this surface

Using the boundary conditions (1) and (2) as follows,

$$D_n \left(\frac{dn}{dx} \right)_{x=0} = S_n n(0) \quad (2.)$$

yields

$$\left(\frac{D_n}{L_n} - S_n \right) n_1 + \left(\frac{D_n}{L_n} + S_n \right) n_2 = -N \left(\frac{1}{1 - \frac{1}{\alpha^2 L_n^2}} + \frac{1}{\alpha D_n (1 - \frac{1}{\alpha^2 L_n^2})} \right) \quad (2.)$$

and

$$n(x_j) = 0 \quad (2.)$$

yields

$$\left(e^{\frac{1}{L_n} x_j} \right) n_1 + \left(e^{-\frac{1}{L_n} x_j} \right) n_2 = \frac{N e^{-x_j}}{\alpha D_n (1 - 1/\alpha^2 L_n^2)} \quad (2.)$$

Solving (2.18) and (2.19) simultaneously for n_1 and n_2 obtain the following expressions

$$n_1 = \frac{-e^{-\frac{1}{L_n} x_j} N \left[1 - \frac{1}{2 L_n^2} + \alpha D_n \left(1 - \frac{1}{2 L_n^2} \right) \right] - \left(\frac{D_n}{L_n} - S_n \right) \alpha D_n \left(1 - \frac{1}{\alpha^2 L_n^2} \right)}{e^{-\frac{1}{L_n} x_j} \left(\frac{D_n}{L_n} - S_n \right) + \left(\frac{D_n}{L_n} + S_n \right) e^{\frac{1}{L_n} x_j}} \quad (2.)$$

$$n_2 = \frac{e^{\frac{1}{L_n} x_j} \left[1 - \frac{1}{1/\alpha \frac{2}{L_n^2}} + \frac{1}{D_n (1 - 1/\alpha \frac{2}{L_n^2})} \right] + \left(\frac{D_n}{L_n} - S_n \right) \frac{N e^{-\frac{1}{\alpha \frac{2}{L_n^2}}}}{\alpha D_n}}{e^{\frac{1}{L_n} x_j} \left(\frac{D_n}{L_n} + S_n \right) e + \left(\frac{D_n}{L_n} - S_n \right) e} \quad (2)$$

with the following notations employed,

$$x'_n = \frac{x_n}{L_n}; \quad y_n = \frac{x_j}{L_n}; \quad a_n = \frac{S_n L_n}{D_n}; \quad b_n = \alpha L_n$$

$n = n(x'_n, \lambda)$ becomes as follows where λ -dependence comes α and N .

$$n(x'_n, \lambda) = \alpha(\lambda) \tau_n N(\lambda) \left\{ \frac{1}{b_n^{\frac{2}{2}-1}} \left[e^{-x'_n} e^{(1-b_n)y_n} - e^{(1-b_n)x'_n} \right] + \left[\frac{a_n+1}{b_n^{\frac{2}{2}-1}} (e^{(1-b_n)y_n} - 1) - \frac{1}{b_n+1} \right] \cdot \frac{\sinh(x'_n - y_n)}{\cosh y_n + a_n \sinh y_n} \right\}$$

for $b_n \neq 1$.

In a similar manner, applying boundary conditions (2) and one obtains

$$p(x'_p, \lambda) = \alpha(\lambda) \tau_p N(\lambda) \left\{ \frac{1}{b_p^{\frac{2}{2}-1}} e^{-x'_p} \left[e^{(-b_p)y_p} - e^{(1-b_p)x'_p} \right] + \left[\frac{a_p+1}{b_p^{\frac{2}{2}-1}} (e^{(1-b_p)(z-y_p)} - 1) - \frac{1}{b_p+1} \right] \cdot \frac{\sinh(x'_p - y_p) e^{-b_p z}}{\cosh(z-y_p) - a_p \sinh(z-y_p)} \right\}$$

for $b_p \neq 1$.

The notations used here are

$$x'_p = \frac{x}{L_p}; \quad y_p = \frac{x_j}{L_p}; \quad z = \frac{d}{L_p}; \quad a_p = \frac{S_p L_p}{D_p}; \quad b_p = \alpha L_p$$

τ_n and τ_p are the life times and D_n , D_p the diffusion coefficients for minority carriers in the p- and n- layer respectively. $L_n = (D_n \tau_n)^{\frac{1}{2}}$, $L_p = (D_p \tau_p)^{\frac{1}{2}}$ are the diffusion lengths and S_n , S_p are the surface recombination velocities at the p- and n-type surfaces. x is the distance from the line exposed p-type surface and x_j is the distance from the surface to the p-n junction which is assumed to be infinitesimally

Since equations (2.22) and (2.23) are indeterminate for the case $b (= \alpha L) = 1$, their forms for this case are obtained by taking the limit as $b \rightarrow 1$ and found to be as follows.

$$n(x'_n, \lambda) b_n \rightarrow 1 = \frac{1}{2} \alpha(\lambda) \tau_n N(\lambda) \left\{ -(y_n - x'_n) e^{-x'_n} + \left[(a_n + 1) y_n + 1 \right] \frac{\sinh(y_n - x'_n)}{\cosh y_n + a_n \sinh y_n} \right\} \quad (2.24)$$

and

$$p(x'_p, \lambda) b_p \rightarrow 1 = \frac{1}{2} \alpha(\lambda) \tau_p N(\lambda) \left\{ (x'_p - y_p) e^{-x'_p} - \left[(a_p + 1) (z - y_p) + 1 \right] \frac{\sinh(x'_p - y_p) \cdot e^{-z}}{\cosh(z - y_p) - a_p \sinh(z - y_p)} \right\} \quad (2.25)$$

Equations (2.22), (2.23), (2.24) and (2.25) can be evaluated after the material constants and dimensions are determined. This can be readily done on prepared solar cells for all of the quantities except τ_n and τ_p .

2.2.2. Evaluation of the photocurrent density

The gradient of the minority carrier distributions near the junction due to photon absorption gives rise to a current across the junction. The magnitude of these currents can be evaluated from equations 2.23 and 2.24 as follows.

The electron current density, $j_n(\lambda)$, from the p-layer is obtained by

$$j_n(\lambda) = qD_n \left(\frac{dn}{dx} \right)_{x=x_j} \quad (2)$$

which yields

$$j_n(\lambda) = qN(\lambda)b_n \left\{ \frac{1}{b_n+1} e^{-b_n y_n} + \frac{1}{b_n^2-1} \cdot \frac{e^{(1-b_n)y_n} - b_n + a_n (e^{(1-b_n)y_n} - 1)}{\cosh y_n + a_n \sinh y_n} \right\}$$

for $b_n \neq 1$ (2)

and

$$j_n(\lambda)b_n \rightarrow 1 = \frac{1}{2}qN(\lambda) \left\{ e^{-y_n} - \frac{1+(1+a_n)y_n}{\cosh y_n + a_n \sinh y_n} \right\}$$

The corresponding hole current density, $j_p(\lambda)$, from the n-layer is obtained by

$$j_p(\lambda) = -qD_p \left(\frac{dp}{dx} \right)_{x=x_j}$$

which yields

$$j_p(\lambda) = -qN(\lambda)b_p \left\{ \frac{1}{b_p+1} e^{-b_p y_p} + \frac{e^{-b_p z}}{b_p^2 - 1} \right. \\ \left. \frac{e^{-(1-b_p)(z-y_p)} - b_p + a_p}{\cosh(z-y_p) - a_p} \frac{e^{-(1-b_p)(z-y_p)} - 1}{\sinh(z-y_p)} \right\}$$

for $b_p \neq 1$

and

$$j_p(\lambda)b_p \rightarrow 1 = -\frac{1}{2}qN(\lambda) \left\{ e^{-y_p} - e^{-z} \frac{1 - (1+a_p)(z-y_p)}{\cosh(z-y_p) - a_p \sinh(z-y_p)} \right\}$$

Equations (2.30) and (2.31) reduce, for the case of ohmic contact covering the back surface of the wafer ($S_p \rightarrow \infty$) to the following expressions.

$$j_p(\lambda) a_p \rightarrow \infty = -qN(\lambda) b_p \left\{ \frac{1}{b_p + 1} e^{-b_p y_p} - \frac{e^{-b_p z}}{b_p^2 - 1} \cdot \frac{e^{-(1-b_p)(z-y_p)} - 1}{\sinh(z-y_p)} \right\} \quad (2)$$

for $b_p \neq 1$

and

$$j_p(\lambda) a_p \rightarrow \infty = -\frac{1}{2} N(\lambda) \left\{ e^{-y_p} - e^{-z} \frac{e^{z-y_p}}{\sinh(z-y_p)} \right\} \quad (2)$$

for $b_p = 1$

The total light generated current density j_L is then given as

$$j_L = \int_0^\infty \left[j_n(\lambda) + j_p(\lambda) \right] d\lambda \quad (2)$$

2.2.3. Collection efficiency (spectral response)

The collection efficiency which is defined as the ratio of electron-hole pairs separated by the electric field of the junction to the total number of electron-hole pairs generated and designated as η_{coll} is given as

$$\eta_{coll}(\lambda) = \frac{j_n(\lambda) + j_p(\lambda)}{qN(\lambda)(1 - e^{-\alpha(\lambda)d})} \quad (2)$$

where the term in parenthesis in the denominator takes account of the fraction of photon transmitted through the wafer.

This collection efficiency takes into account only the incomplete collection of the electron-hole pairs by diffusion to the p-n junction.

The over-all collection efficiency $\Gamma(\lambda)$ which takes account of the reflection losses on the surface, the incomplete absorption of photons ($h\nu < E_g$) and the incomplete collection of the electron-hole pairs by diffusion to the p-n junction could be defined as

$$\Gamma(\lambda) = \frac{j_n(\lambda) + j_p(\lambda)}{qN_{inc}} \quad (2.35)$$

The relationship between the photon flux in the light beam $N_{inc}(\lambda)$, and that actually entering the semiconductor, $N(\lambda)$ is determined by the reflection coefficient $r(\lambda)$ as follows

$$N(\lambda) = N_{inc}(1-r(\lambda)) \quad (2.36)$$

Inserting (2.37) into (2.35) we obtain

$$\eta_{coll} = \frac{j_n(\lambda) + j_p(\lambda)}{qN_{inc}(1-r(\lambda))(1-e^{-\alpha(\lambda)d})} \quad (2.37)$$

combining (2.36) and (2.38)

$$\Gamma(\lambda) = \frac{j_n(\lambda) + j_p(\lambda)}{qN_{inc}} = (1-r(\lambda))(1-e^{-\alpha(\lambda)d})\eta_{coll} \quad (2.38)$$

Improvement in collection efficiency for any given material could be achieved by increasing the minority carrier life time in the p- and n-materials, by using materials with higher electron and hole mobilities or by using materials with somewhat smaller absorption coefficients in the peak region of the solar spectrum.

2.3. Losses due to the I-V characteristics

2.3.1. The voltage factor (V.F.)

The amount of energy utilized in the generation of electron-hole pairs is equal to the potential difference between the top of the valence band and the conduction band. The largest recoverable voltage is however the open-circuit voltage which is lesser than the energy gap, mainly due to the following two reasons.

Firstly, the barrier height is determined by the difference in Fermi levels in the n- and p-type material on both sides of the junction. These Fermi levels are dependent on temperature and impurity concentration, and are normally located within the forbidden gap in the case of non-degenerate semiconductors. Hence the barrier height (V_b) is less than the energy gap (E_g).

Another reason is the fact that a voltage equal to V_b can only be obtained at extremely high injection levels which are not reached by photon absorption from direct sunlight.

From the I-V characteristics of a p-n junction the maximum open-circuit voltage (V_{oc}) is given as

$$V.F. = V_{oc} = \frac{AKT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \quad (2.40)$$

where I_0 is saturation current, I_L is the light generated current or the short-circuit current (I_{sc}) and A is the so called perfection constant of the I-V characteristic.

The voltage factor (V.F.) is then defined as

$$V.F. = \frac{V_{oc}}{E_g} = \frac{AKT}{qE_g} \ln \left(\frac{I_L}{I_0} + 1 \right) \quad (2.4)$$

From diffusion theory of p-n junctions as given by [17]

$$A = 1$$

and

$$I_0 = qe^{-39E_g} \cdot \left(\sqrt{\mu_p/\tau_p} \cdot 1/N_d + \sqrt{\mu_n/\tau_n} \cdot 1/N_a \right) \quad (2.4)$$

where A and I_0 are exclusively determined by material constants and temperature. N_d , N_a are the donor and acceptor densities; μ_n , μ_p are electron and hole mobilities; and τ_n , τ_p are electron and hole life times.

2.3.2. The curve factor (C.F.)

The maximum power can be extracted from a photovoltaic device at that point for which the largest rectangle can be inscribed into the I-V characteristics (curves). This point is given by

$$P_{max} = V_{max} I_{max} \quad (2.4)$$

and the curve factor is given by

$$\begin{aligned}
 \text{C.F.} &= \frac{V_m I_m}{V_{oc} I_{sc}} \\
 &= \left[1 - \frac{AKT}{qV_{oc}} \ln \left(1 + \frac{qV_m}{AKT} \right) \right] \cdot \left[1 - \frac{I_o}{I_{sc}} \exp \left(\frac{qV_m}{AKT} \right) \right]
 \end{aligned}
 \tag{2}$$

where V_{oc} is given by equation (2.40), and

$$\begin{aligned}
 V_m &= \left(1 + \frac{qV_m}{AKT} \right) \exp \left(\frac{qV_m}{AKT} \right) \\
 &= \frac{V_{sc}}{I_o} + 1 \\
 &= \exp \left(\frac{qV_{oc}}{AKT} \right)
 \end{aligned}
 \tag{2}$$

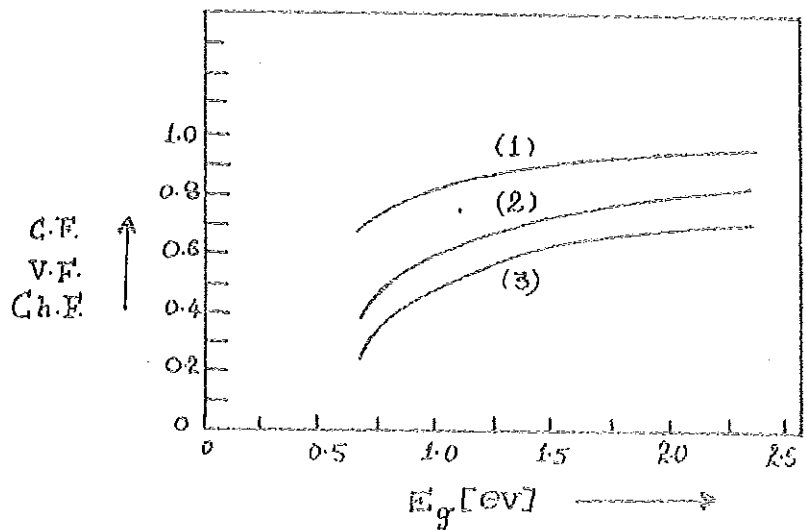


Fig.2.5. V.F., C.F., and Ch.F. versus width of energy gap. Published data by Wolf [16].

The curve factor as well as the voltage factor are determined by the saturation current I_0 . Better values of V.F. and C.F. are obtained at larger energy gaps as can be seen from figure

The characteristic factor (CH.F.) which is defined as the product of V.F. and C.F. is given by

$$\text{CH.F.} = \text{V.F.} \times \text{C.F.} = \frac{V_m I_m}{E_g I_{sc}} \quad (2.4)$$

The characteristic factor could be improved by proper choice of materials with suitable energy gap and selection of proper doping levels.

2.3.3. Series resistance losses

The output current from a solar cell is given by

$$I_R = I_0 (e^{B(V - IR_s)} - 1) - I_L, \quad B = \frac{q}{AKT}, \quad |B| = V^{-1} \quad (2.5)$$

If $BIR_s < 1$, a first-order approximation in the exponential yields

$$I_R = \frac{I}{1 + I_0 B R_s e^{BV}} \quad (2.6)$$

where $I = I_R (R_s = 0) = I_0 (e^{BV} - 1) - I_L$

Following Wolf and Prince, the power obtainable from a solar cell is

$$P = I_R V = I_R \frac{1}{B} \ln \left(\frac{I_L + I_R}{I_0} + 1 \right) + I_R^2 R_s \quad (2.7)$$

where $I_R^2 R_s$ is the power dissipated directly in the series resistance R_s . The first term also bears dissipation due to variation of the I-V curve. Hence it could be imagined a total power dissipation P_{R_s} to exist.

2.4. Conversion efficiency (η) and limit conversion efficiency

(η_{lim})

Combining all the loss factors so far discussed we reach at the so called conversion efficiency, which is the one obtainable in practice.

$$\eta = \frac{P_{out}}{P_{in}} = (V.F.) (C.F.) (1 - P_{R_s}) \frac{q}{hc} \int_0^{\infty} [1 - r(\lambda)] \cdot [1 - e^{-\alpha(\lambda)d}] \eta_{coll}(\lambda) P_{in}(\lambda) d\lambda \cdot \left[\int_0^{\infty} P_{in}(\lambda) d\lambda \right]^{-1}$$

where $P_{in}(\lambda)$ is the light power incident on the solar cell surface in a narrow range $d\lambda$ around the wavelength λ ; the first integral is the total short-circuit current density and the second integral in the denominator is the total light incident.

The limit conversion efficiency η_{lim} , is an idealized efficiency. It describes a theoretical efficiency which is dictated only by basic phenomena and not by technique factors.

This idealized efficiency can never be reached, but is a most important tool for the evaluation of different materials and approaches.

The limit conversion efficiency η_{lim} is derived based on the assumptions that there is no reflection loss, and no recombination loss. Assumed also are complete absorption of photons, 100% collection of generated electron-hole pairs. η_{lim} is given

$$\eta_{lim} = \frac{(V.F.) (C.F.) \frac{q}{hc} \left[\int_0^{\text{cut off}} P_{in}(\lambda) d\lambda \right]}{\int_0^{\infty} P_{in}(\lambda) d\lambda} \quad (2.5)$$

CHAPTER 3

CHARACTERISTICS OF ELECTRICAL CONNECTIONS AND
ENVIRONMENTAL INTERFACES

Experimenters usually adhere to two directions of philosophy in reporting calculated efficiencies, i.e., some report values corrected for the contact area losses and others do not. Uncorrected values are reported on philosophy that these describe what the cell can actually deliver, while efficiency values corrected for the contact area losses are reported on the philosophy that these are the inherent efficiencies of the devices without the human factors of contact design and process technology. Actually, it seems reasonable that both values should be reported at the same time which would eliminate ambiguity.

For enhancing the corrected-value line of thought it is essential to assess the characteristics of each of the component layers of a generalized thin film solar cell. The two semiconductor layers have been discussed in the previous chapter. In this chapter the layers which serve as electrical connections and environmental interfaces will be discussed.

3.1. Electrical contacts

3.1.1. The transparent electrical contacts

The one side of the cell which is thought to receive illumination is made up of optically transparent material which must provide an ohmic contact. At the same time it shall have a high current carrying capability so as to minimize the series resistance of the total structure.

Generally, there are two basic types of transparent contacts: 1) conducting oxides such as tin oxide (TO) and mixture of indium and tin oxide (ITO), 2) open metallic grid such as silver, silver-titanium-paladium mixtures, gold, graphite, copper, and chromium.

The transparent contact serves also as a substrate in the case of glass which is either covered with a conducting oxide or a metal-grid pattern. In this case the light will pass through the substrate either directly falling on the absorber-generator or going through the collector-converter to the absorber-generator.

3.1.2. Opaque electrical contacts

This electrical contact is meant to provide an electrical connection to the side of the solar cell opposite the transparent contact. It must be ohmic and low in resistivity. Hence, the metal substrates such as copper, steel are usually preferred.

The copper layer serves also as a substrate for growing the semiconductor layers, and also as an encapsulant for one side of the device which has been developed. When serving as a substrate, it must have a coefficient of expansion that matches reasonably to its neighbouring semiconductor layers. Another important characteristic is the optical reflectivity at the contact to allow multiple passes of light through the absorber-generator.

3.2. The encapsulant

Solar cells must be protected from hostile environment by an encapsulant. At the same time reflection losses introduced by this layer must be controlled. Hence, application of transparent encapsulants on one side of the solar cell meets this demand of reflection loss minimization.

In the case where the encapsulant is applied over the transparent contact, glasses have proven to be most successful. These glasses can be formed from a broad range of compounds based on silicon, oxygen, and other elements. In systems commonly used today, these glasses are bonded to a solar cell after fabrication. But development of integral encapsulants in the range of 5 μm thick directly applied to the solar cell is also taking place.

In the case of a glass substrate which also serves as a transparent contact, the encapsulant can be an opaque layer

or layers of metal, such as copper and lead, with the primary purpose of preventing environmental degradation.

3.3. Antireflection coatings

3.3.1. Analysis of reflection loss from semiconductor

The fraction of energy reflected on a boundary of a semiconducting material is determined by the reflection factor given as

$$r = \frac{\text{reflected light intensity}}{\text{incident light intensity}} = \frac{J_r}{J_o} \quad (3)$$

while the remaining

$$J(x) = J_o (1-r)e^{-\alpha x} \quad (3)$$

is transmitted to a distance x in the given material where $r = r(\lambda)$ or $r(\omega)$ and $\alpha = \alpha(\lambda)$ or $\alpha(\omega)$ are the reflection and absorption spectrums of the material.

The absorption coefficient α is related to the absorption index n_k by the expression

$$\alpha = \frac{4\pi n_k}{\lambda} \quad (3)$$

n stands for refractive index.

From the electromagnetic theory of light the reflectivity for normal incidence can be expressed in terms of refractive and absorption indices as follows.

$$r = \frac{(n-1)^2 + n^2 \kappa^2}{(n+1)^2 + n^2 \kappa^2} \quad (3.4)$$

combining equation (3.3) and equation (3.4), we obtain

$$r = \frac{(n-1)^2 + \frac{\lambda^2}{16\pi^2} \alpha^2}{(n+1)^2 + \frac{\lambda^2}{16\pi^2} \alpha^2} \quad (3.5)$$

As is manifested in equation (3.5) the reflectivity r depends on the absorption coefficient α such that the reflectivity increases with the increase in the absorption coefficient. For $\kappa \gg 1$; the incident light is almost completely reflected. This explains good light reflection by metals (metallic luster). Hence, if a substance absorbs light intensively in some spectral interval it will also intensively reflect in the same spectral interval. However, it follows from the same equation that reflection could also take place in the absence of absorption i.e., $r \neq 0$ for $\alpha = 0$, yielding the following explicit dependence of reflectivity on refractive index.

$$r_{\alpha=0} = \frac{(n-1)^2}{(n+1)^2} \quad (3.6)$$

The majority of semiconductor materials under study for solar cells have high indices of refraction of the order of two to four as are shown in Table (3.1) below [18].

TABLE 3.1

Refractive index of some semiconductors

substance	n	substance	n
c(diamond)	2.417	InSb	3.988
Si	3.446	GaP	2.970
Ge	4.006	GaAs	3.348
InP	3.370	GaSb	3.748
InAs	3.428	AlSb	3.188

This high order of refraction index results in reflection from a planar surface in the range of 25 to 35%. In order to minimize this high reflection loss, antireflection layers are necessary.

3.3.2. Reduction of Reflection

There are two primary approaches in attempting to reduce these reflection losses.

The first technique is texturing the surface of the semiconductor so as to cause multiple reflections for incoming photons, reducing the net photon loss. The second technique is to use multilayer antireflection coatings so as to reduce reflection by both index matching and interference effects. A combination of the two techniques have also been successful.

utilized. It involves texturing the semiconductor layer and providing an antireflection layer on top of this material.

The deposition of several layers of appropriate indices of refraction and thickness can extend the width of the reflection minimum to near zero over a wide region, therefore leading to a highly minimized reflection loss.

The five essential layers of a solar cell described above provide all the necessary functions for the direct conversion of sunlight to electricity utilizing the photovoltaic effect.

CHAPTER 4

DESIGN OPTIONS

Any photovoltaic solar cell basically consists of the generator and the collector-converter layers. On this basis are three design options for a single system device; namely

1) The homojunction solar cell: where the collector-converter is a semiconductor material which is of the same as the absorber-generator,

2) The heterojunction solar cell: where the collector-converter is a semiconductor material different from the absorber-generator layer, and

3) The Schottky-barrier solar cell: where the absorber-generator is a semiconductor layer and the collector-converter is a combination of a metal and an insulator or simply metal. Energy band diagrams for these designs are shown in figure.

These three design options enable us to produce at least four distinct solar cells where each of them kick the advantage of a specific material property and/or resolve a specific problem.

4.1. Characteristics of homojunction solar cells

In such types of solar cells, the absorber-generator and collector-converter are made up of the same material except that the collector-converter must be of opposite conductivity to

of the absorber-generator thus providing the barrier potential for photovoltaic energy. This barrier is a classical p/n homojunction as in the case of the common silicon single crystal cells. The number of semiconductors in which p/n homojunctions can be fabricated is limited to silicon, most $A^{III}B^V$ semiconductors, CdTe, ZnTe, CuInS₂, CuInSe₂ and a few others.

The homojunction has the advantage that the theory is quite well understood and some of the metallurgical and electrical problems such as thermal coefficient of expansion matching, lattice matching and electron affinity matching are overcome.

The primary problems with homojunction tends to be surface recombination at the most heavily doped surface which faces sunlight. Good thin film cells of the homojunction type have to be fabricated from any other semiconductor because the diffusion process commonly used to form p/n homojunction do not work well for thin films. Diffusion down grain boundaries is difficult to control. In addition, inexpensive thin film deposition techniques like vacuum evaporation do not as a rule allow deposition of films of both conductivity types in which resistivity and other important photovoltaic parameters can be readily controlled to the degree required for efficient solar cells.

All solar cells can be described by the following equation [19].

$$j = \sum j_{oi} \left(e^{\frac{qV}{n_i KT}} - 1 \right) - j_L(V). \quad (4)$$

Generally for a homojunction, $n_i = 1$ and j_o is given as

$$j_o = q \left(\frac{D_n}{L_n} n_{op} + \frac{D_p}{L_p} p_{on} \right) \quad (4)$$

where q is the magnitude of the electronic charge, D_n the electronic diffusion coefficient, and L_n the diffusion length of electrons in the p-type material. D_p and L_p are the corresponding quantities for holes in the n-type material, n_{op} and p_{on} are equilibrium density of electrons and holes in p-type and n-type material, respectively. j_L is the light generated current, and may be voltage dependent.

The diffusion coefficients and lengths are related to material properties through the equation

$$D = \frac{KT\mu}{q} \quad (4)$$

$$L^2 = \frac{KT\mu\tau}{q} = D\tau \quad (4)$$

where μ is the mobility and τ the recombination life time of the minority carriers.

Another mechanism which can occur is space charge region recombination with $n_i = 2$ and $j_o \sim e^{-E_g/2KT}$. The $n_i = 1$ case dominates the most efficient solar cells.

Another advantage of a homojunction is that the degradation mechanism due to interdiffusion of elements is reduced.

4.2. Characteristics of heterojunction solar cells

In a heterojunction solar cell, the collector-converter is chemically different from the semiconductor material of the absorber-generator. One of these materials is n-type and the other is p-type producing the necessary barrier voltage.

Most successful thin film cells are of the heterojunction type because they are easier to fabricate using thin film deposition techniques (Procedures) and there are many semiconductor pairs which can, in principle, produce good solar cells. Usually the band gaps for these two materials differ significantly.

In the front-wall configuration, the small band gap material is illuminated first. Since most of the absorption will take place in this material it will control the current collected and the maximum voltage achievable. But sometimes illumination is also carried through the larger band gap material, called the back-wall configuration.

The primary advantage of the heterojunction structure is that it allows materials which can not be doped both p-type but other outstanding features to be utilized for very high energy conversion efficiencies, most of which are opposite conductivity type, matching electron affinities and matching of the lattice

The heterojunction equation has been described by Roth [20] and the dominant term in equation (4.1) has the same form as the homojunction equation with $n_1 = 1$ and j_0 given by

$$j_0 = qN_c S_I e^{-\phi/KT} \quad (4)$$

where S_I is the interface recombination velocity and

$$S_I \approx V_{th} \frac{\sigma \Delta a}{a^3} \quad (4)$$

where V_{th} is the thermal velocity of electrons (or holes), σ the capture cross-section, Δa is the difference in lattice constant between the two materials, a is the average lattice constant in the plane of the junction, and ϕ is an activation energy given by the relation

$$\phi = E_{g1} - \delta_1 qV_{D1} - (\chi_2 - \chi_1) \quad (4)$$

where χ_1 and χ_2 are the electron affinities of the respective semiconductors, δ_1 the separation between the valence band and the fermi level in the p-type material, and V_{D1} the diffusion voltage in that material.

The main disadvantage of heterojunction structure is that in contrast to the homojunction one, it shows a degradation mechanism due to diffusion of the component materials. Another disadvantage is revealed in the energy band diagram shown in figure (4.1b). The electron affinities of the two semiconduc

are such that a spike appears in the conduction band. This is an undesirable situation because the spike represents a barrier to the flow of minority electrons from the p-side to the n-

There are a variety of heterojunctions under critical investigation today. To mention a few of them, are heterojunctions such as CdS/Cu₂S, CdTe/CdS, CdS/CuInSe, InP/CdS, CuTe/CdTe, ZnCdS/Cu₂S.

4.3. Schottky-barrier solar cells

Schottky-barrier solar cells consist of a metallic collector-converter on a semiconductor absorber-generator. This metallic contact can be on either a p-type or an n-type semiconductor. In such cells the magnitude of the diffusion potential or barrier height is determined by the difference between the work function of the metal and of the semiconductor. Now it happens that the magnitude of the diffusion potential encountered in metal-semiconductor (M-S) cells is not high enough to provide the voltages needed to extract optimum solar energy conversion performance from the semiconductor.

M-S cells can be illuminated through the metal. In such case the metal must be very thin in order to avoid both absorption and heavy reflection losses. But if such cells are to be illuminated through the semiconductor side the metal should be of high reflectivity so as to reflect back into the semiconductor allowing thinner absorber-generator layers.

Schottky-barrier solar cell is more advantageous than either the homojunction or heterojunction since it is conceptually a simple device system, merely a semiconductor for the absorption of light, a generator and a metal barrier. However, the mechanisms which control the behaviour of the Schottky barrier solar cell are not as well understood as the homojunction.

The main consideration is the condition of the surface of the semiconductor, the presence or absence of an oxide or passivation layer between the metal and the semiconductor. Unless extreme precautions are taken, compound formation between the metal and the semiconductor forms a junction, and the properties of the device are largely controlled by the properties of this layer.

The Schottky-barrier solar cells is fairly described by the following equation:

$$j = A^*T^2 e^{-q\phi_E/KT} \left(e^{\frac{qV_j}{n_i KT}} - 1 \right) \quad (4)$$

with

$$j_0 = A^*T^2 e^{-q\phi_B/KT}$$

where $A^* = 120 \left(\frac{m^*}{m_0} \right) \frac{A^*}{\text{cm}^2}$ K is the Richardson constant

modified by optical phonon scattering quantum mechanical reflection, and tunneling of carriers at the metal-semiconductor interface, and m^* is the effective mass tensor for the relevant carrier.

energy bands in the semiconductor. n_1 is the perfection factor of the j-v characteristic of Schottky-barrier cells, and is usually greater than unity.

In general, Schottky barrier cell efficiencies are very much lower than the maximum values achieved for hetero- or homojunction cells of the same material.

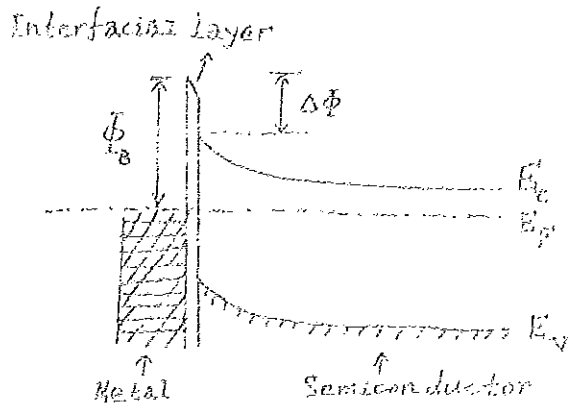
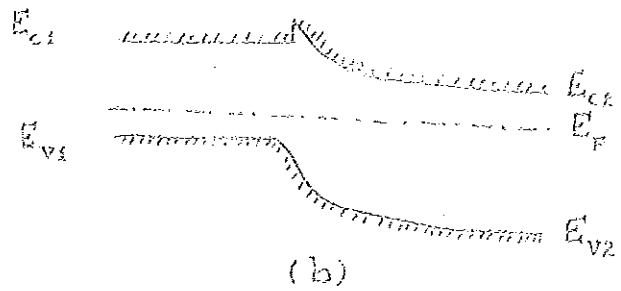
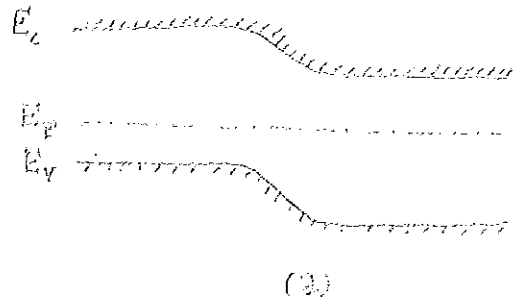
4.4. Metal-insulator-semiconductor cells

One of the problems of the Schottky-barriers, the reduction of open-circuit voltage, can be eliminated by using an insulating layer between the absorber-generator semiconductor and the metallic collector-converter. This insulator and metal structure serves as the collector-converter and generally yields higher open-circuit voltage than the simple Schottky configuration.

In 1974, Shewchun et al. [21] described a metal-insulator-semiconductor (M-I-S) cell consisting of a thin ($\approx 60 \text{ \AA}$) transparent layer of Aluminium deposited over a silicon single crystal wafer on whose surface an even thinner ($\approx 20 \text{ \AA}$) layer of natural silicon oxide had been grown prior to deposition of Aluminium. The oxide suppresses emission of electrons from the metal into the semiconductor but it is thin enough so that light generated in the semiconductor minority carriers can flow from the semiconductor into the metal by tunneling.

The insulator, as mentioned above, can be an oxide or another insulating material such as a compound formed between the metal and the absorber-generator semiconductor. These devices are described as M-I-S or M-O-S depending on whether the insulator is an oxide or any other insulator.

A significant improvement over the M-I-S cell was described in 1976 by Dubow et al. [22] who replaced the transparent metal film with a conducting transparent metal film with a conducting transparent semiconductor was a mixture of indium and Tin oxide (ITO).



Energy band diagrams of

- a) p-n homojunctions
- b) p-n heterojunctions
- c) MS junctions

Fig.4.1. Energy band diagrams for three possible designs of solar cells.

CHAPTER 5

SOLAR CELL MEASUREMENTS

The purpose of this chapter is to describe circuits and experimental set-ups for solar cell parameters determination. Results obtained in measurement of various parameters of FD-Si of Soviet origin solar cell are presented in form of tables and graphs and conclusions are being drawn. Attention has been paid in order to establish the circuits which are able to measure parameters of different solar cells, from Si-single crystal cell of high efficiency to thin film low cost cells of low efficiency. The range of parameters which are covered by the circuits is given by the instruments available. Thus, for example, the frequency response measurement is confined to the visible spectrum range only instead of the infrared and ultraviolet ones.

5.1. Efficiency measurement

Efficiency, η , of a solar cell is defined as the ratio of the maximum electrical power output, P_{\max} of the cell to the incident solar power, I , on the cell.

$$\eta = \frac{P_{\max}}{I} \quad (5.1)$$

where P_{\max} and I are determined by the following procedures

5.1.1. Electrical power output determination

Efficiency, among all other parameters, is the most important quantity of a solar cell. Hence establishing wa and means of measuring this quantity experimentally is vital. To this end the circuit diagram shown in figure 5. was set up to measure the electrical power output of the cell.

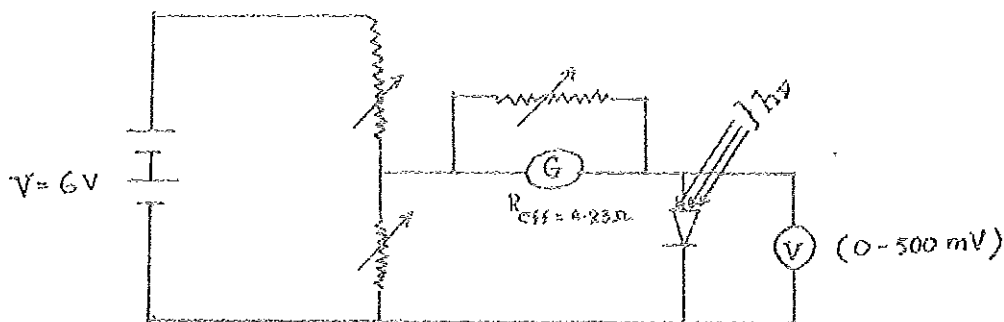


Fig.5.1. Circuit diagram for determination of electrical power output of a solar cell.

Current versus voltage readings were taken at three different levels of illumination. Illumination on the solar cell was varied by means of neutral spectral density grey filters. Results obtained from the experiment are shown in tables 5.1, 5.2, and 5.3 where the corresponding I-V curves are depicted in figure 5.2.

As calculated from the I-V data, the maximum power output of the cell for the corresponding levels of solar illumination is 1.43 mW, 0.61 mW, 0.14 mW.

Table 5.1 I-V characteristic measurement of Si-s
cell (Fd-K Si) direct sunlight illumination
Time was (10.20-10.30 a.m.)

V [mV]	I [mA]	P [mW]
0	10.50	0.00
40	10.50	0.42
56	10.12	0.57
72	9.78	0.70
87	9.45	0.82
58	9.00	0.52
121	8.70	0.10
133	8.43	0.11
150	8.10	0.12
164	7.76	1.27
179	7.45	1.33
200	7.00	1.40
221	6.40	1.41
237	6.05	1.42
251	5.70	1.43
260	5.49	1.42
276	5.10	1.41
291	4.72	1.37
303	4.40	1.33
313	3.11	1.29

Table 5.1 (continued)

V [mV]	I [mA]	P [mW]
330	3.65	1.20
351	3.02	1.06
338	2.48	0.84
385	2.00	0.76
393	1.70	0.67
402	1.40	0.56
408	1.20	0.49
411	1.00	0.41
416	0.80	0.33
435	0.00	0.00

Table 5.2 I-V characteristic measurement of Si-s cell (Fd-K Si) under sunlight illumination (Intensity reduced by one-fourth). Time was 10.30-10.35 a.m.

V [mV]	I [mA]	P [mW]
10	3.06	0.31
30	3.04	0.91
72	3.02	0.22
112	3.01	0.34
135	3.00	0.41
153	2.99	0.46
172	2.94	0.51
190	2.86	0.54
244	2.40	0.59
280	2.17	0.61
301	1.85	0.56
307	1.67	0.51
320	1.52	0.49
354	1.28	0.45
341	1.10	0.38
335	0.90	0.30
380	0.00	0.00

Table 5.3 I-V characteristic measurement of Si-s cell (Fd-K Si) under sunlight illumination (Intensity reduced by one-sixteenth). (Time was 10.40-10.45 a.m.).

V [mV]	I [mA]	P [mW]
0	0.75	0.00
30	0.74	0.02
72	0.73	0.05
113	0.73	0.08
144	0.72	0.10
175	0.72	0.13
191	0.71	0.14
196	0.71	0.14
343	0.00	0.00

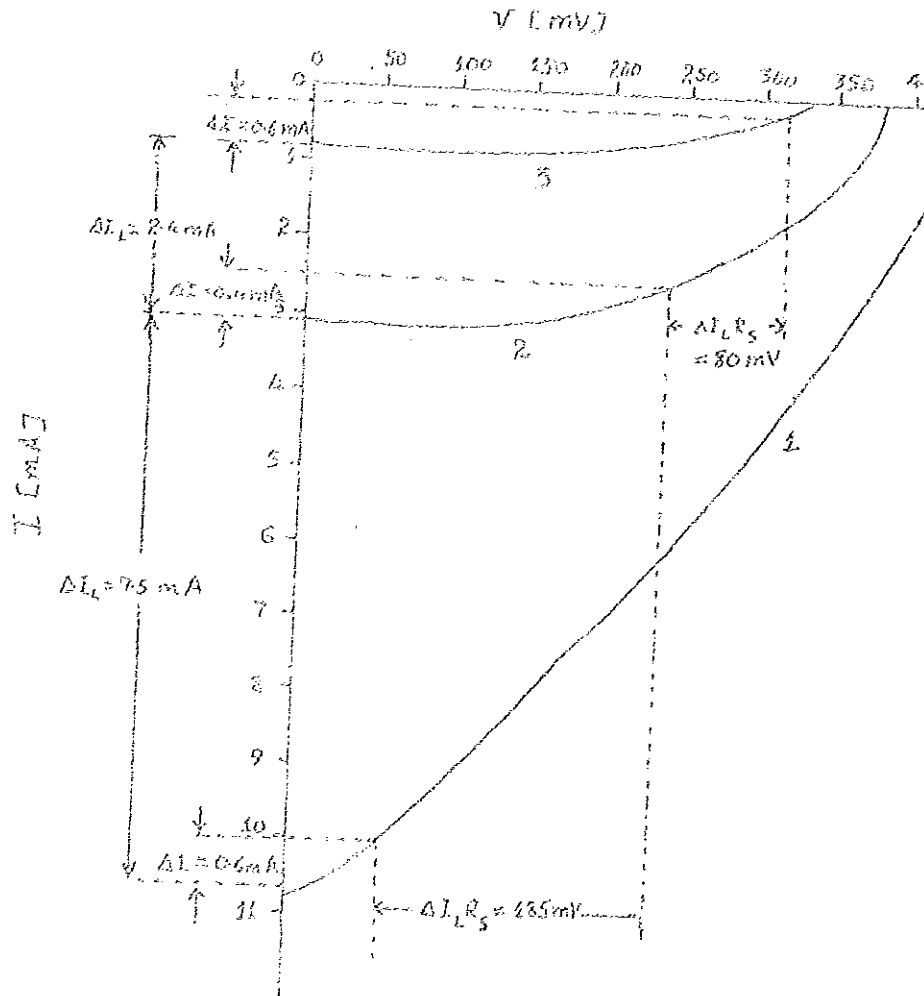


Fig. 5.2. Photovoltaic output characteristics.

5.1.2. Incident solar power determination

The estimate of the incident solar irradiance at the earth's surface is 95.6 mW/cm^2 for the sun directly overhead. The solar irradiance varies due to the following main factors,

- 1) The geographical location of the place mainly the latitude,
- 2) Seasonal variation, i.e., whether the sun is overhead the tropics or at the equator and
- 3) The time of the day.

To take care of all these factors, we make use of the air mass (AM) concept which is defined as the path length of radiation through the atmosphere considering the vertical path at sea level as unity. The air mass is given by

$$AM = \frac{1}{\cos z} = \frac{1}{\cos L \cos D \cos H + \sin L \sin D} \quad (5)$$

where z is the angle between a line vertical to the observer and a line through the observer and the sun. L is the latitude of the place, D is the day's declination and H is the hour angle.

- 1) The local latitude (L) for Addis Ababa is 9°
- 2) The day's declination of the sun (D) is given by

$$D = 23.5^\circ \sin \left(\frac{n\pi}{365} \right) \quad (5)$$

where n is the number of days from vernal equinox measured or minus according to whether the sun is north or south of equator, respectively. On June 7, $n = 79$ days.

$$\text{Thus, } D = 23.5^\circ \sin \frac{79\pi}{365} = 14.8^\circ.$$

3) The hour angle H is determined by taking the arctan of the ratio of the height, h , of a given object to the average length of its shadow, \bar{I} .

$$H = \tan^{-1} \left(\frac{h}{\bar{I}} \right) \quad (5)$$

where $h = 12.0$ cm, $\bar{I} = 9.75$ cm and $H = \tan^{-1} \left(\frac{12}{9.75} \right) = 50.9^\circ$

Therefore,

$$\begin{aligned} \cos z &= \cos L \cos D \cos H + \sin L \sin D \\ &= \cos 9^\circ \cos 14.8^\circ \cos 50.9^\circ + \sin 9^\circ \sin 14.8^\circ \\ &= 0.6422. \end{aligned}$$

$$AM = \frac{1}{\cos z} = 1.6.$$

The solar irradiance for the above calculated air mass can be obtained from the graph shown in figure 5.3 which is found in any standard book of astronomy, and is 86 mW/cm^2 .

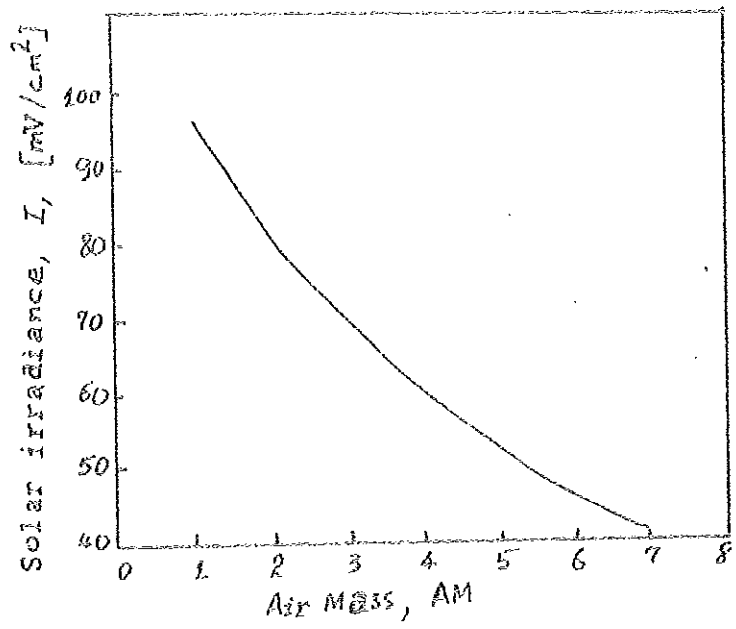


Fig.5.3. Solar irradiance versus Air Mass

5.1.3. Calculation of efficiency

Once the electrical power output of the cell and the solar irradiance on the cell were determined its conversion efficiency could be obtained as follows.

$$\eta = \frac{\text{max. Power output/unit area}}{\text{Solar-irradiance}} \times 100 = \frac{P_{\text{max}}}{AI} \times 100.$$

Diameter of the solar cell, $d=1.1$ cm; hence had a total area $A = \frac{\pi d^2}{4} = 0.95 \text{ cm}^2$. The maximum power generated under visible light illumination is $P_{\text{max}} = 1.4$ mW. Thus,

$$\eta = \left(\frac{P_{\text{max}}}{AI} \right) \% = 1.8\% .$$

When the illumination was reduced by one-fourth, $P_{\text{max}} = 0.6$ mW

and
$$\eta = \left(\frac{P_{\text{max}}}{AI} \right) \% \cdot 4 = 3.0\% .$$

When the illumination was again reduced by one-sixteenth

$$P_{\text{max}} = 0.14 \text{ mW}$$

and
$$\eta = \left(\frac{P_{\text{max}}}{AI} \right) \% \cdot 16 = 2.7\% .$$

Such a low efficiency is attributed to the internal series resistance of the cell. From the I-V characteristic shown in figure 5.2 an easy and accurate determination of this internal resistance could be made according to the method employed by Martin Wolf and Hans Rauschenbach [23].

The two photovoltaic output characteristics are translated against each other by the amounts ΔI_L (Light generated current) and $\Delta I_L R_S$ (potential drop across the internal resistance) in y- and x- directions, respectively. Two corresponding points on the two characteristics show a displacement with respect to each other, which is identical to the two translations of the coordinate systems. The displacement parallel to the ordinate gives the value of ΔI_L . Since the displacement parallel to the abscissa equals $\Delta I_L R_S$, the value of the internal resistance R_S is readily obtained.

One practical approach to this procedure is to choose an arbitrary interval ΔI from the short-circuit current which is marked on the first characteristic. It is frequently found convenient to choose ΔI so as to obtain a point in or near the knee of the characteristic. The same ΔI value is used for finding a second corresponding point on the second characteristic curve.

Applying this method of correlation a shift of $\Delta I = 0.5$ mA is made from the short current $I_{sc} = 10.5$ mA and $I_{sc} = 3.1$ mA on curves (1) and (2) corresponding voltage shifts $\Delta I_L R_S = 185$ mV and $\Delta I_L R_S = 80$ mV are obtained from the curves. The change in the light generated current between characteristic curves (1) and (2) is 7.5 mA. Hence the internal resistance of the cell which of course includes that of the ammeter is obtained to be $R_S = \Delta I_L R_S / \Delta I_L$. If correction of the internal resistance of the ammeter ($R_A = 4$ ohms) is made the internal resistance of the cell alone becomes $R_S = 40$ ohms.

Similarly performing the same translation on curves (2) and (3), and effecting the correction due to the ammeter the internal resistance of the cell happens to be 29.2Ω .

The curves in figure 5.2 indicate that the internal resistance can severely affect the performance of photovoltaic cells as solar energy converters. The maximum power output of a solar cell is given by the area of the largest rectangle that can be drawn inside the photovoltaic output characteristic. The area of such a rectangle increases with increasing sharpness of the knee in the photovoltaic output characteristic. Internal series resistance causes a successively larger rounding of the curve at increasing light intensities.

The knee of each of the characteristic curves represents the maximum power point voltage. As revealed in the curves obtained, this point decreases with increasing light intensity due to the finite internal series resistance of the cell.

The effect of the internal series resistance on the short circuit current of the cell is also evident. In actuality, the short circuit current must be directly proportional to the increase in light intensity. But as shown in the photovoltaic characteristic curves, for a constant increase of illumination the increase in short circuit current decreases. Hence, it is not correct to assume that the short-circuit current is always equal to the light generated current at every level of illumination.

5.2. Spectral response measurement

Another important parameter of a solar cell is its response to various wavelength radiations. Since the solar spectrum consists of various wavelength radiations it is instructive to study the behavior of spectral response of a solar cell.

Spectral response is defined as the short-circuit current per incident light power versus wavelength or photon energy. Some authors like Cusano [24] define the spectral response as the short-circuit current per number of incident photons.

As the light source it was used an incandescent tungsten filament lamp operating at 5.6v. The temperature of the filament was determined earlier by Letemeskel to be 2400K [25].

The spectral emittance, $M(\lambda, T)$ for tungsten is given by the following formula

$$M(\lambda, T)_t = e(\lambda, T) M(\lambda, T)_{bb} \quad (5.1)$$

where $e(\lambda, T)$ is tungsten spectral emissivity and $M(\lambda, T)_{bb}$ is the spectral emittance of a black body radiator. The spectral dependence of $e(\lambda, T)$ for $T = 2400K$ is indicated in figure 5.1 according to Wyszecchi and Shiles [26].

Grating monochromator (Coleman 6A Junior Spectrophotometer) was used for spectral response measurement. Short-circuit

photocurrent was measured at different wavelengths within the range of 400 nm to 700 nm. Photocurrent as low as 10^{-10} A could be measured with Griffin d-c amplifier and electrometer available. Results obtained are tabulated in table 5.4 and shown in figure 5.5.

The spectral energy distribution derived from figure 5.1 was used to normalize the cell photocurrent (Table 5.4) and given in table 5.5. Results of relative spectral response measurements show that Si solar cells are highly responsive within the visible spectrum as shown in figure 5.5b.

Table 5.4 Spectral response of Fd-K Si solar cell

λ [nm]	I_a [arbitrary unit]	E [ev]
400	0.60	3.10
410	0.80	3.02
420	1.00	2.96
430	1.40	2.89
440	1.60	2.82
450	2.00	2.76
460	2.60	2.70
470	2.80	2.64
480	4.00	2.59
490	5.00	2.53
500	6.00	2.48
510	6.80	2.43
520	8.40	2.39
530	10.0	2.34
540	12.0	2.30
550	14.0	2.26
560	17.6	2.22
570	20.0	2.18
580	24.0	2.14
590	27.0	2.10
600	30.4	2.07
610	34.0	2.03
620	38.0	2.00
630	43.0	1.97

Table 5.4. (continued)

λ [nm]	I_a [arbitrary unit]	E [ev]
640	47.0	1.94
650	51.0	1.91
660	56.0	1.88
670	60.0	1.85
680	64.0	1.83
690	69.0	1.80
700	73.5	1.77

Table 5.5 Normalized spectral response of Fd-K Si solar cell

λ [nm]	$y = \log \left(\frac{M_{2400}}{M_{300}} \right)$	10^y	I_a [arbitrary unit]	$I_a / 10^y$
400	0.45	2.82	0.60	0.21
420	0.65	4.47	1.00	0.22
440	0.83	6.69	1.60	0.24
460	1.00	10.00	2.60	0.26
480	1.13	13.34	4.00	0.30
500	1.27	18.84	6.00	0.32
520	1.38	23.71	8.40	0.35
540	1.48	29.85	12.00	0.40
560	1.58	37.58	17.60	0.47
580	1.65	44.67	24.00	0.54
600	1.73	53.09	30.40	0.57
620	1.80	63.10	38.00	0.60
640	1.88	74.99	47.00	0.63
660	1.93	84.14	56.00	0.67
680	1.98	94.41	64.00	0.68
700	2.03	105.93	73.50	0.69

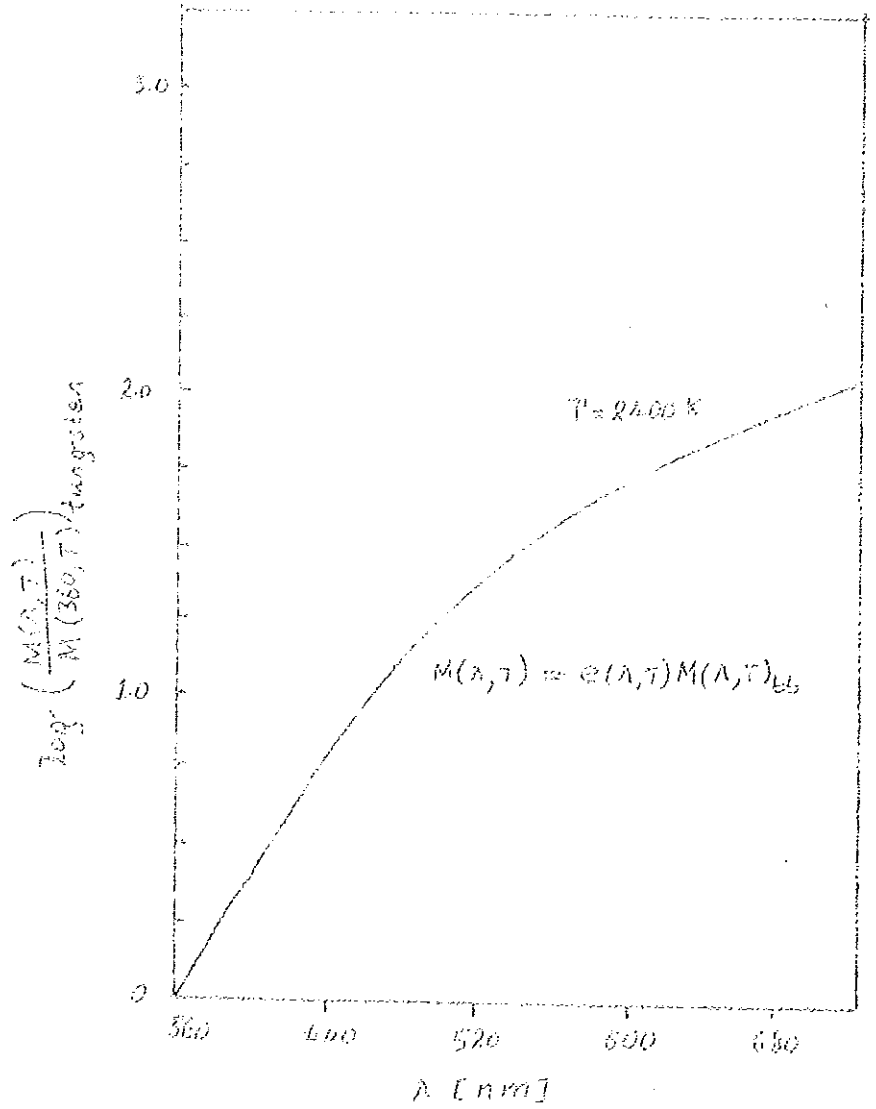


Fig.5.4. Relative spectral energy distribution of incandescent tungsten lamp.

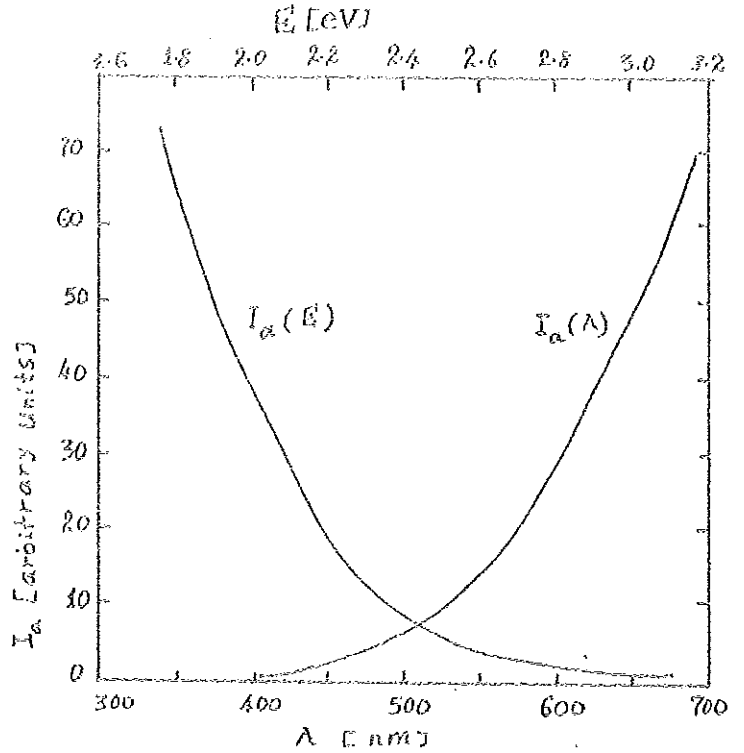


Fig.5.5a. Spectral response of FD-K Si solar cell.

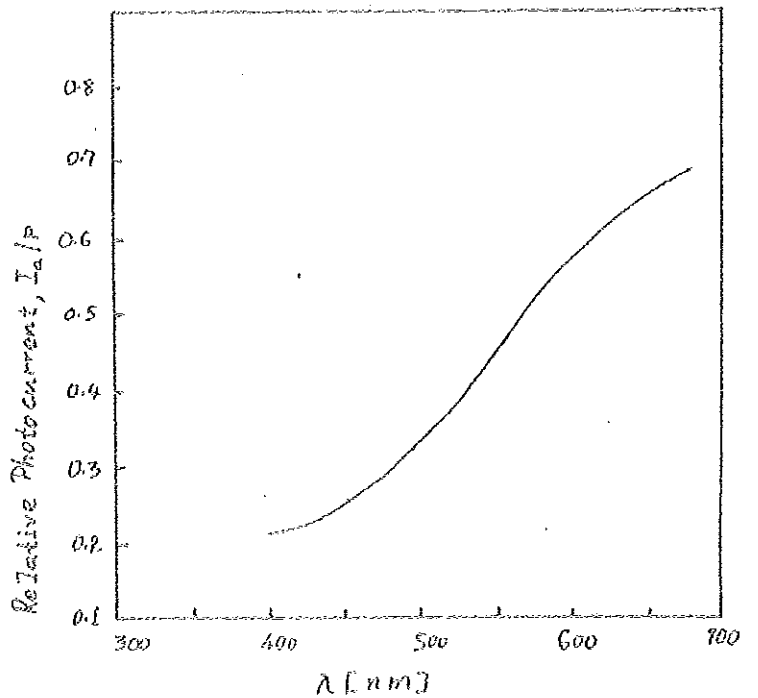


Fig.5.5b. Normalized spectral response FD-K Si solar

5.3. Current-voltage curve measurement (dark conditions)

A standard I-V curve circuit diagram used in our measurement is drawn in figure 5.6 below.

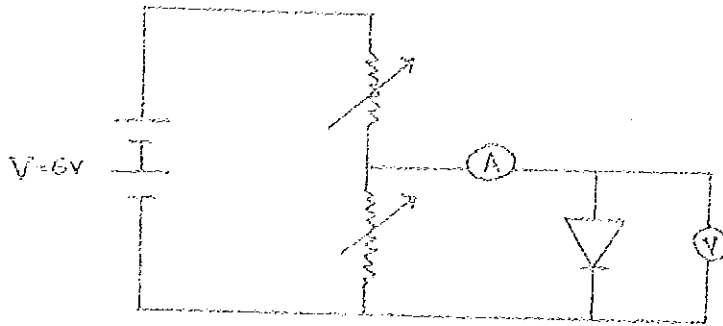


Fig.5.6. Circuit diagram for I-V curve measurement in the dark.

Resistor decades boxes were used to control the solar cell bias. Forward current was measured by a d.c. milliammeter. Reverse current of the cell is very low (Si solar cell has very low saturation current). For this measurement the Weston Soffron Walden light spot galvanometer was used. Sensitivity is $72.5 \text{ mm}/\mu\text{A}$, internal resistance is 75Ω . Bias was measured by Phillip Harris digital multimeter of $200 \text{ K}\Omega/\text{V}$ internal resistance. Corrections on the voltmeter current have been made.

The measurement was performed under dark conditions. Results are given in table 5.6 and in figure 5.7. The curves have different units for both forward and reverse bias.

Table 5.6 I-V characteristic measurement of Si-sol
cell (Fd-K Si) in the dark

Forward bias		Reverse bias	
V [volts]	I [mA]	-V [volts]	I [nA]
0.00	0.00	0.00	0.00
0.35	0.20	0.10	70.00
0.40	0.90	0.20	100
0.46	1.20	0.30	110
0.50	2.30	0.40	120
0.64	9.00	0.50	140
0.70	12.0	0.60	150
0.80	26.0	0.70	160
0.90	50.5	0.80	165
1.00	82.5	0.90	170
		1.00	172
		1.20	180

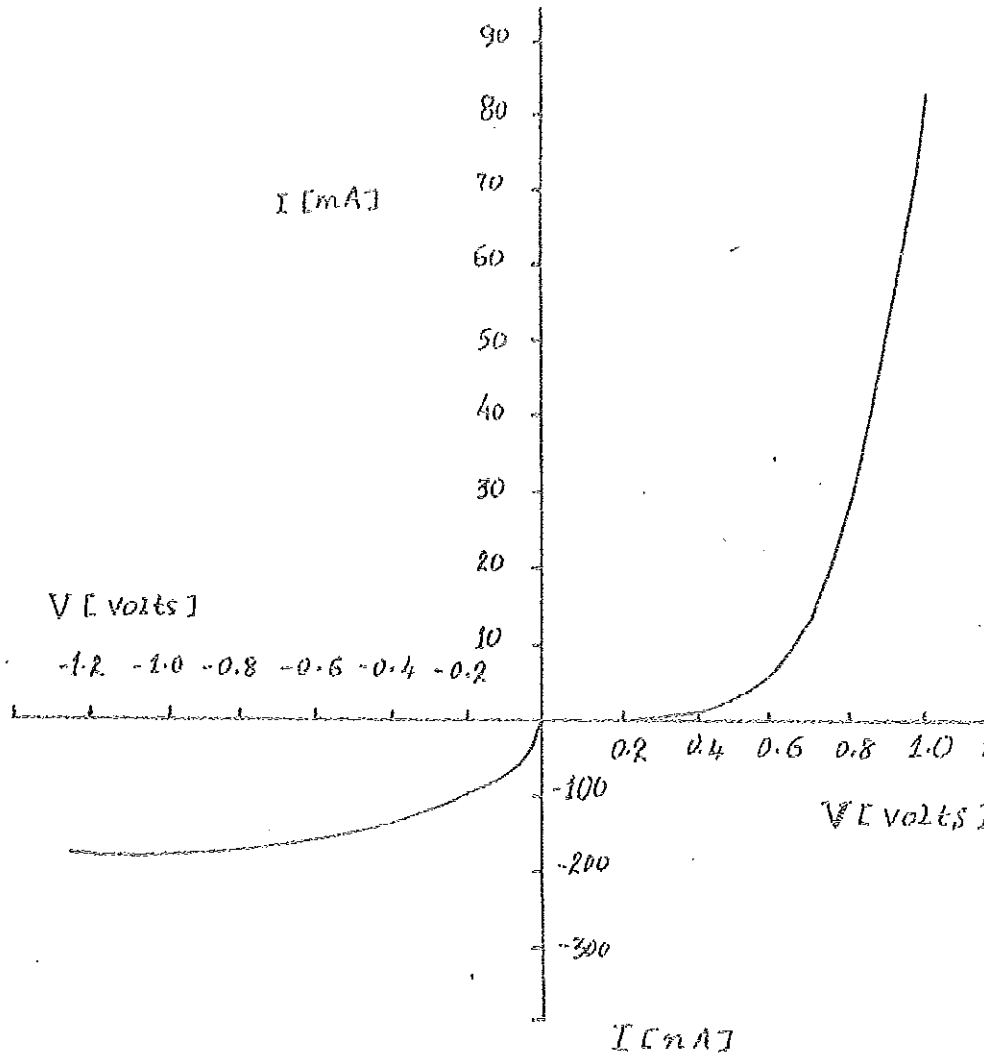


Fig.5.7. I-V characteristic curve of FD-K Si solar in the dark.

5.4. Capacitance-voltage curve measurement

The depletion layer of a junction device represents a capacitor whose capacitance per unit area is given as

$$c = \frac{dQ}{dV} \quad (5)$$

where dQ is the infinitesimal increase in charge per unit area upon an infinitesimal change of the applied voltage dV .

For a plane abrupt junction the depletion layer capacitance per unit area is given by

$$c = \frac{\epsilon_s}{W} \quad (5)$$

where ϵ_s is permittivity of a semiconductor and W is the depletion layer width. The width is given by

$$W = \sqrt{\frac{2\epsilon_s (N_D + N_A)}{qN_A N_D} (V_{bi} \pm V - \frac{KT}{q})} \quad (5)$$

where V_{bi} is the built in potential and N_B, N_A are the donor/acceptor densities respectively [27]. K is the Boltzmann constant, T is absolute temperature and q is the electronic charge.

In the case of a one-sided abrupt junction, the above expression reduces to

$$W = \sqrt{\frac{2\epsilon_s V_{bi}}{qN_R}} \quad (5)$$

where N_B is equal to the donor density N_D or the acceptor density N_A depending on whether $N_A \gg N_D$ or vice versa.

Combining equations (5.7), (5.8) and (5.9) one obtains

$$C = \sqrt{\frac{q\epsilon_s N_B}{2(V_{bi} \pm V - \frac{KT}{q})}} \quad (5)$$

or

$$\frac{1}{C^2} = \frac{2}{q\epsilon_s N_B} (V_{bi} \pm V - \frac{KT}{q}) \quad (5)$$

Equation (5.11) can be used for the built-in potential (barrier height) determination. The term KT/q is negligible (for 300 K, it is equal to 26 mV).

Differentiating equation (5.11) with respect to V , one obtains

$$\frac{d(\frac{1}{C^2})}{dV} = \pm \frac{2}{q\epsilon_s N_B} \quad (5)$$

It is clear from equation (5.11) that a C-V curve measurement furnishes a lot of important data of the junction. Hence, measurement was performed with an impedance bridge (1650-A General Radio Corporation). The measurement frequency was 1 KHZ. Reverse cell bias was within the range of 0 to 6 volts. circuit diagram is shown in figure 5.8.

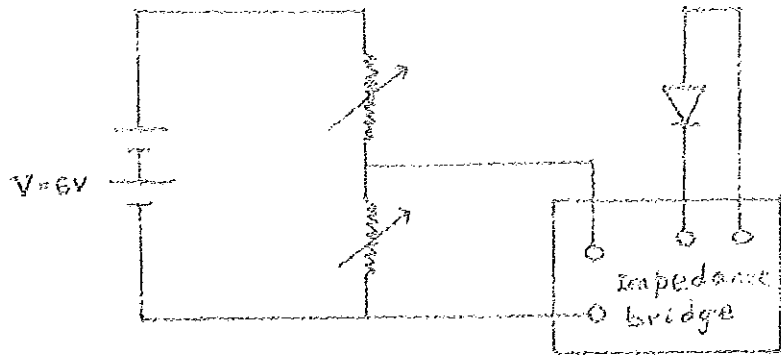


Fig.5.8. Circuit diagram for C-V curve measurement

The measurement was performed under dark and illumination conditions. C-V and $\frac{1}{C^2}$ -V curves are shown in figures 5.9 and 5.10 as produced from tables 5.7 and 5.8.

The built-in potential V_{bi} is determined by extrapolating the straight line curve (1) to the positive voltages axis. It is found to be 0.75 eV. From the slope of the straight line curve the donor density N_D in the cell is obtained to be $3.53 \times 10^{19} \text{ m}^{-3}$.

Table 5.7 C-V characteristic measurement of Ed-K Si so
cell in the dark

$-V$ volts	C nF	c nF/cm ² ($c=C/A$)	$\frac{1}{c^2}$ cm ² /nF ²
0.50	1.79	1.88	0.28
1.00	1.49	1.57	0.41
1.50	1.32	1.39	0.52
2.00	1.19	1.25	0.64
2.50	1.10	1.16	0.75
3.00	1.02	1.07	0.87
3.50	0.96	1.01	0.98
4.00	0.94	0.99	1.02
4.50	-	-	-
5.00	0.86	0.89	1.22
5.50	-	-	-
6.00	0.78	0.82	1.48

Table 5.8 C-V characteristic measurement of Fd-K S
solar cell under illumination by Tungst
filament

$-V$ [volts]	C [nF]	C [nF/cm ² ($C = C/A$)	$\frac{1}{C^2}$ [cm ² /nF] ²
2.50	1.84	1.94	0.27
3.00	1.54	1.62	0.38
3.50	1.26	1.43	0.49
4.00	1.24	1.30	0.59
4.50	-	-	-
5.00	1.05	1.10	0.82
5.50	-	-	-
6.00	0.94	0.99	1.02

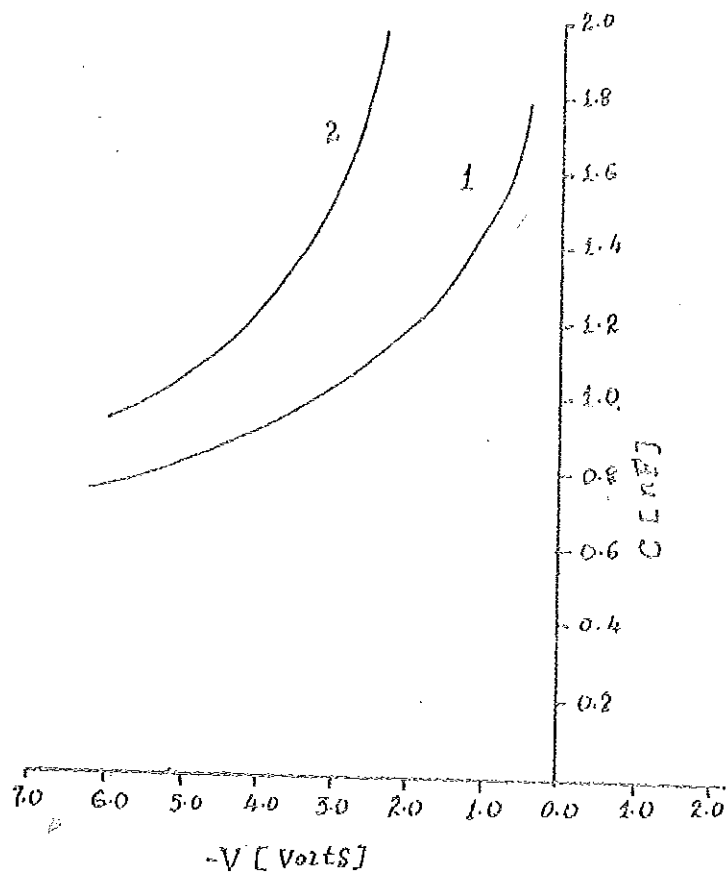


Fig.5.9. C-V characteristic curves.

- 1) In the dark
- b) Illuminated.

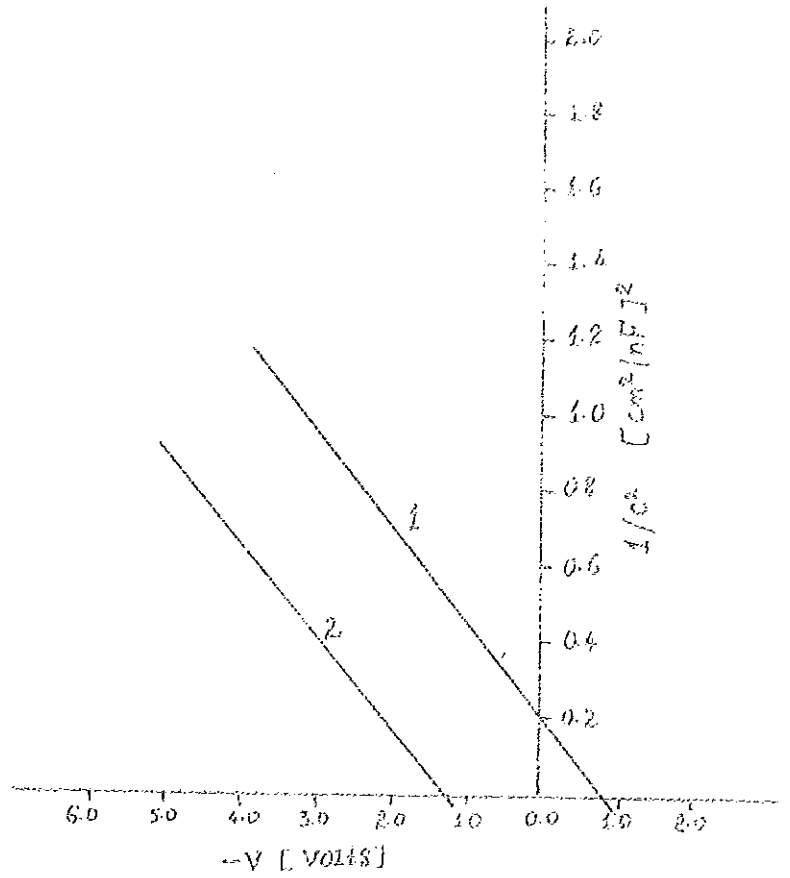


Fig. 5.10. $\frac{1}{i^2}$ versus V curve.

CONCLUSION

In this work the establishment of circuits which are a to measure parameters of different solar cells, from Si-sin crystal cell of ihigh efficiency to thin film low cost cell of low efficiency was made possible. However, due to the inavailability of thin film solar cells in the country, it not possible to apply our circuits for parameters measurement of these types of cells. Thus, measurements only on single solar cell have been carried, and the results obtained are acceptable.

In the efficiency measurement, the dependence of efficiency on the internal series resistance of cells has been observed to vary with light intensity.

In the spectral response measurement, despite the limited range of the spectrophotometer used, a good information about the sample cell could be drawn; i.e., the cell shows a rapid increase in spectral response upto the middle of the visible range, then the increase is gradual.

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