IC/85/313
INTERNAL REPORT

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

SOLAR CELL CONCENTRATING SYSTEM

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MIRAMARE – TRIESTE
November 1986

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1. INTRODUCTION

In the recent years, the development of new and renewable energy sources has been taking place in order to achieve self sufficiency in energy. Amongst different ways of utilizing natural energies, power generation from solar energy by photovoltaic process is the one, which has been introduced recently. Solar cell (device converting sunlight to electricity) is clean and infinite energy sources. A variety of solar cells have been designed and their performance studies have been reported by several workers(1-5). Truly speaking, very little amount of work has been done, so far, as fabrication of efficient and economic solar cell is concerned. Solar cells, no doubt, could convert about 14% of terrestrial sunlight into electricity with a maximum conversion efficiency of 18.6% for single crystal silicon and 9.14% for amorphous silicon(6). But the high cost factor alongwith several non-awareness about the technicalities, is a major obstackle to the wide spread use of solar cell technology. There are several gaps even today which require decicated work to be filled in this direction(7). Several reviews are available in the literature(8-10) but none of these discuss comprehensively the problems of designing a cost affective highly efficient system with accesible technicalities. As suggested by various workers engaged in this field(11-20) an alternate way to lower the cost per watt from solar cells is to concentrate sunlight on the cells with the use of solar concentrator, thus replacing the high priced cell area with low priced concentrator material. An earlier study demonstrated that the use of photovoltaic concentrator, to increase the output power per cell subsequently reduced the photovoltaic system cost. But it is worth mentioning that many more problems gets involved when solar cells are used with high concentration of energy(21). In fact very little research attention has been focussed on the design and development of a system to keep the temperature of the cells low enough. There are a very few experimental studies on photovoltaic solar cells at high concentration. Consequently it was concluded that a detailed experimental program should be undertaken to make this unique concept of photovoltaic cell at high concentration more cost effective and efficient. This study reviews fabrication techniques and testing facilities for different solar cells under concentration which have been developed and tested. It is also aimed to examine solar energy concentrators which are prospective candidate for photovoltaic concentrator system. This may provide an impetus to the scientists working in the area of solar cell technology.

2. PHOTOVOLTAIC EFFECT(25)

In order to understand the concept of electricity generation directly from sunlight, it is almost essential to understand the physics of photovoltaic effect. The photovoltaic effect is generation of an electromotive force as a result of the absorption of ionizing radiation. There exist a variety of materials showing fairly good response for photovoltaic effect. But amongst different materials, semiconductors have been shown to be the best and most appropriate for photovoltaic process. Properties of the semiconductors have been reviewed very nicely by Charles E. Backus(1977)(26). But the concept of substrate doping level, minority carrier life time etc, are still to be examined. A brief description of the characteristics of the semiconductors materials is discussed below under the heading suitable materials for photovoltaic effect.

2.1 Suitable Materials for Photovoltaic Effect(26)

As mentioned above, the photovoltaic effect can be observed in a variety of materials but the materials that have shown the best performance in sunlight are the semiconductors. The energy of the electrons alongwith their distribution in the outermost or highest energy bands determine their potential for use in photovoltaic effect. For this reason semiconductor (intrinsic/Extrinsic) are the best suited materials for this effect. By adding small amounts of dopants to semiconductors crystals, it is possible to choose, the dominant type of conduction in a material. The conduction mechanism in semiconductors (Intrinsic and Extrinsic) can be explained with the help of Fig.(1). The second point worth consideration in this regard are the optical characteristics. For efficient conversion of solar energy into electricity photon from the sun has to be absorbed to create free electrons with higher energies. In general, the incoming photons with energies greater than the forbidden energy gap, can be completely absorbed by an electron and than jump the gap whereas photons with energies less than the band gap are all lost since they cannot excite any electrons. After the absorption of photons, the electronhole pairs created are seperated by p-n junction (Fig.2). Finally, when excitation of electrons to the conduction band takes place, it is the transport characteristic of the material that check the probability of recombination of charges with opposite potentiality. In other words there must be an electric field to induce these carrier to flow out of the semiconductor to do useful work. The mobility life time, mean free path and diffusion lengths of the charge carrier are other terms that plays on very important role for the transpotation of charge carriers. Table (1) shows possible potential materials for photovoltaic effect.

3. SOLAR CELL

The solar cell (Fig. 3) is the basic component of any photovoltaic system, fabricated from semiconductors materials thus converting a fraction of the solar energy into electrical energy. A variety of solar cells have been fabricated, tested and evaluated by scientists all over the world, particularly in developed countries. Moreover, with patronage of government of different countries and of different agencies, good technical reports on this aspects are available today. The solar cells of various types(Fig-4) which have been tested successfully include silicon solar cells, cadmium supphide/copper sulphide cells , gallium arsenside cells, etc. Recently a very good review of the progress in photovoltaic conversion, in terms of photovoltaic R&D, related key technologies, various Techno-economic aspects of using amorphous silicon as solar cell material and introduction of some possible new approaches, has been presented by Yoshihiro Hamakawa(38). As mentioned above the technical feasibility for photovoltaic system is well established but still it seems to hancicapped by economic considerations. No device is useful unless it is economically viable. The economic feasibility of solar cells, however, depends on the optimization of the trade off between useful electrical energy under specified design conditions and low material and fabrication cost. Keeping this point in mind an attempt has already been made towards this goal by the use of solar cells under concentrated sunlight. The concentrating devices lower the area requirement of the actual photovoltaic cells. It has been reported that the present costs per watts can be considerably reduced because the area of the cells is reduced inversely proportional to the concentration ratio. During the last few years, many aspects of the optical, thermal and electrical characteristics of photovoltaic concentration systems have been studied(27-34). It has been reported that the ultimate attractiveness of concentration system primarily depends upon the cost of the concentration surface per unit area. The present study reviews methods to produce solar energy concentrators which have been developed and tested for photovoltaic concentrator. It is also aimed to examine solar cells which are best suited under concentrated sunlight.

4. PHOTOVOLTAIC CELLS WITH SUNLIGHTS CONCENTRATION

The high cost; the primary limitation and major stumbling block for solar cell's wide spread use, is tackled by replacing high cost cell area with low cost optical areas. Photovoltaic concentrator technology will make photovoltaic systems competative for a significant number of large scale power generation applications. The development of photovoltaic concentrator includes:

a) Design and development of solar cells for high solar intensity(35).

b) Developing solar energy concentrators

c) Development of concentrators components

d) Experimental appratus for cooling of photovoltaic cells at high concentration.

e) To design a low cost suntracking structures and

f) Finally to generate facilities for the through evaluation of the photovoltaic concentrators.

In this article authors have tried at their level best to study/review a few of the above mentioned aspects in details.

4.1 Solar Cell for High Solar Intensity Applications

When the intensity incident on a solar cell is increased the light generated current increases being linearly proportional to the intensity of sunlight on the cell. The efficiency of the solar cell expressed as

$$\eta = \frac{\text{Isc. Voc. FF.}}{\text{Incident Power}} \qquad (1)$$

increases as the log of the intensity of sunlight.

where

Isc = short circuit current

Voc = Open circuit voltage

and FF = Current voltage fill factor

Inspection of the above equation (1), implies that for a solar cell to operate under high solar intensity, it must have the following features:

1) Sufficiently low series resistance
2) Temperature dependence of operative characteristics should be small
3) Absorption coefficient should be high
4) life time of the carriers should be short
5) The structural losses listed below should be minimum
    a) loss through the reflection at the surface
    b) loss through the absorption
    c) loss through recombination process
    d) Electric losses caused by such as sheet resistance, contact resistance, and electrode resistance of the cell.

The special features listed above plays a significant role while selecting a most suitable semiconductor for highly reliable concentrator solar cells with a high conversion efficiency. In addition to the above listed spectral response, the development of a suitable solar all for high solar intensity applications also involves :

1) Studies on cell shape
2) Designing an antireflection coating
3) Designing the grid pattern

4.1.1 Studies on cell shape

In concentrating photovoltaic power generation the shape of the concentrating spot depends entirely upon the nature/type of solar energy concentrator used for concentrating the solar energy. It may be circular, linear/line focus inverted V or wedge focus, etc. For example the concentrating spot is round when ordinary fresnel lenses are used. Therefore, the input area of the solar cell should be designed in the same fashion as that of concentrating spot.

4.1.2 Designing an anti-reflection coating

Anti-reflection coating are used to reduce the reflectance of the cells in a given wavelength range. Anti-reflection coatings must be designed so that the maximum number of photons having energy greater than the energy gap of semiconductor used for the solar cell, passes through without being reflected. A detailed analytical study regarding the design consideration of anti-reflection coating has already been reported by group of scientists working for Kansi Electric Power Co. Inc. in Japan(6). Fig. 7 shows the relationship between the refractive index and the transmission index of an anti reflection coating. It was observed by them that the thickness of the anti-reflection coating which maximizes the number of photons having energy greater than the energy gap of the semiconductor and which pass through into the solar cell without being reflected at the surface in terms of the refractive index n_A of the anti-reflection coating is $d = 150/n_A$ (nm). The possible materials for anti reflection coating are Si_3N_4, ZrO_2, To_2O_3, ITO and TiO_2. After considering the refrective index and etchbility, Si_3N_4 and ITO was concluded to be the best antireflection material.

4.1.3 Designing the Grid Pattern(14)

It is anticipated that when there is a large distance between the contact grids of cell, there is significant voltage drop because of losses due to metal shadowing, resistance in the contacts & diffused layer. It has been observed that at a given current density, as the contacts are moved further apart, the shadowing losses decreases whereas the registance losses increase in both the metal contacts and the diffused layer. It has been observed experimentally(14) that for above losses to be minimum the optimized contact widths & contact seperations for luminescent solar cell under concentration (LSC) has values 25 μm and 850 μm respectively.

Recent experiment have shown that silicon cells can be made to operate under high solar intensity, if the temperature is maintained constant(23). Computer modelling(24) has helped to identify cell design features which lead to optimized cell performance. Moreover, new cell structures namely BSF and HIF have also been identified by computer modelling as cell designs which could lead to increase cell performance at high concentration.

It has also been observed experimentally as well as theoretically that gallium arsenide solar cell with GaAl As/GaAs heteroface structure is the most suitable for its operations under the most highly concentrated sunlight(6). Figure 5 shows a cross-section of GaAs solar cell of this type whereas Fig. 6 shows its energy band diagram. The surface recombination limitation of such a solar cell is prevented by forming a P-GaAl/As layer on the P-GaAs layer. It is because of high demonstrated efficiency and tolerance of higher temperature that makes Gallium arsenide solar cell very attractive for concentrating systems.

4.2 Fabrication Process of Concentrated Solar Cell

literature survey shows that upto a concentration factor of 100 or 50, conventional silicon solar cell are suitable. But for high concentration intensities within operating range of 100°C (or even 200°C), conventional silicon solar cells are no longer suitable. Under such circumstance and for concentration ratio in the range 200 to 1000, galium arsenide cells with GaAl As/GaAs hetero face structure have been concluded to be the best suitable candidate.

Fig. 8 shows the fabrication process for the most potential candidate for solar concentrated solar cell i.e. GaAl As/GaAs solar cell in the hetero face structure, using liquid phase epitexial growth, CVD and lift-off technique etc.

Gallium arsenide concentrator solar cells were fabricated using n-type GaAs substrate. All depents were introduced with gaseous source diffusion by a liquid phase epitaxy technique. Si_3N_4, an anti-reflection coating is formed on P-GaAl As layer by chemical vapour deposition techniwue. To facilitate the collection of the current, a conducting metal contact is evaporated over the entire surface of the water by vacuum evaporation and collecting fingers are evaporated on the front. Finally P-GaAs layer is formed on the back of the opitaxial water and is removed by etching. Silver is plated on the electrode metal. The GaAs concentrator solar cell with a structure like that shown in Fig. 5 is thus completed by the fabricating process described above.

Similarly the luminescent solar concentrator silicon cells were studied analytically, fabricated and experimentally tested to optimize the cell performance for 600 mm and longer wavelengths. It was reported by Garner et al (1980) that under illunination the projected peak efficiency of this cell at 600 nm is 26%.

5. THEORETICAL CONSIDERATION FOR SOLAR CELL WITH SUNLIGHT CONCENTRATOR.

A good computational model must contain all the important operating perameters that influence the performance of solar cell under high concentration. If actual performance measurements are found to be in good agreement with modell prediction, the model becomes a valuable tool for predicting the performance of the system under investigation. L.W. florschuetz (1975) has developed the mathematical relationship predicting the performance of solar cell in terms of electrical power output per unit absorber area as a function of solar radiation and coolant temperature. A brief description is given below.

Accroding to the model developed by Florschuetz(24), the energy balance equation for absorber can be written as

$$EA_a = \alpha \, Is \, As - Q \qquad (i)$$

where

E = the electrical output per unit absorber area

Aa = Absorber area

Is = solar radiation per unit area of absorber surface

Q = heat-transfer rate

and

$$\alpha = \alpha_c \frac{A_c}{A_a} - \alpha_{nc}\left(1 - \frac{A_c}{A_a}\right) \qquad (ii)$$

here Ac is the absorber portion covered by cell. and are the solar absorptances of the cell covered and non-cell covered portion of the absorber surface. Also the efficiency of the solar cell is given by the expression.

$$EA_a = \eta \; Is \; Ac$$

It is assumed that cell efficiency decreases linearly with all temperature as per relation

$$\eta = \eta_r \left\{ 1 - \beta_a (T_c - T_a) \right\} \qquad \text{(iii)}$$

By combining all the above equations the final expression obtained was of the form.

$$E = \frac{1 - \frac{\alpha I_s \beta}{K_e} - \beta_a (T_o - T_r)}{\frac{1}{I_s \eta_a} \frac{A_a}{A_c} - \frac{\beta_a}{K_e}} \qquad \text{(iv)}$$

This is an expression which gives the electrical power output per unit absorber area, E, as function of Is and coolant temperature (To), with the cell characteristics, cooling system effective-thermal conductance Ke. Using the above formula the electrical output for silicon solar cell was predicted as a function of incident solar radiation. With the increases of solar radiation, the cell operating temperature increases, thus, resulting decrease in cell efficiency.

Moreover, equation (iv) also imples that

$$I_s = \frac{K_e}{\alpha \beta_o} \cdot \frac{A_a}{A_c} \left\{ 1 - \left(1 - \frac{\eta_o A_c}{\alpha A_a}\right)^{1/2} \right\} \qquad \text{(v)}$$

and thus helps in predicting the value of Is at which power output is maximum, for fixed values of α, β_r, Ke and $\eta_r \left(\frac{A_c}{A_a}\right)$ The above equation can also be simplefied as

$$I_s = \frac{K_e}{2\alpha \beta_o} = \frac{K_e (T_c^* - T_o)}{2\alpha} \quad \text{for } E = E_{max} \qquad \text{(vi)}$$

The significant feature of equation (vi) is that it can be used to estimate an approximate upper bound of concentrated solar radiation worth applicable to any system under investigation.

6. SOLAR ENERGY CONCENTRATORS

A solar concentrator is an optical device which is a combination of reflector-receiver system and like most devices is very senstive to spatial imperfections. Solar concentrators can broadly be classified into three groups. The first are planar, nonoconcentrating, flat plate type popularily known as collector-booster system which provides moderate concentration. The second group are focussing collectors which produce a high density of radiation at a line or point focus. The third concentrator's type achieves a concentration multiplication in the range of 1-10 and are popularly known as non-imaging concentrators.

Point focus concentrators have circular symmetry and are used when high concentration is required whereas line focus concentrators have cylindrical symmetry and are generally used when medium concentration is sufficient. A variety of geometric shapes have been proposed in each category. Although a lot of research work has been reported by scientists, but still there are several problems remains unanswered(27-34). For example, there is no definite demorcation line between moderately and strongly concentrating system. In these following paragraphs various types of solar concentrators are described in brief.

6.1 Non-Tracking or seasonally Adjusted Type Solar Concentrators(39)

Non tracking concentrators are cylindrical or V-trough concentrators (Fig. 9). The detailed analysis conducted by Tabor(40) and then by Mannan and Bannarot(41) had already concluded that a concentration of approximately 3 can be obtained with east-west mirror if tilt is varied with seasons. According to Grasso etal a V-trough collector is just a compound parabolic concentrator (cpc) for concentrator ratio of approximately 3 (i.e. c = 2.65). Thus v-trough concentrator having specular side walls are best suited for then film solar cell(30).

6.2 Plane Mirrors as Sun Tracking Concentrators.

There are some special cases of use of narror mirror strips in formation such as Russel's(42) and strip mirror concentrator made by phillips company(43). These concentrators produce much higher concentrations. An array of directable mirrors (Fig. 10) has been used as photovoltaic solar concentrator(29).

6.3 Non-imaging Concentrators

The non-imaging concentrators when properly designed are able to give moderate concentration without continuous tracking. This close of concentrators are generally called CPCs, even though some of them are not exactly parabolic in shape. The CPC shown in Fig. (11a) was independantly discovered by Baranov and Malnikov in USSR(44), Hinlorberger and Winston in USA(45), and Plike in Germany(46). There are at least four types of CPC with different receiver shapes(47) i.e. a flat receiver, a fin receiver, a inverted V-receiver or dedge receiver and tabular receiver as shown in Fig. 11(b).

b) linear fresnel lens
c) curved base linear fresnel lens
d) Inverted Vee-type linear fresnel lens and
e) linear fresnel lens with different groove width.

Recently detailed investigations both analytically and experimentally were conducted by Hastings and Allum(48), Nelson(49) Szulmayer(50), Kritchman(51,52) Cosby(53) etc. on such solar concentrator. Nelson etal(49) have analytically studied the performance of a seasonally adjusted or one axis-tracked linear fresnel lens concentrators. Very recently(21), a through investigation regarding use of silicon cell under solar energy concentration using circular fresnel lens, in Indian climatic conditions has been conducted under the supervision of Prof. Chopra.

6.6 Parabolic Trough Concentrator

Parabolic concentrator (Fig. 13) can be built either as a trough (two dimensional geometry, line focus, one axis tracking) or as a dish (three dimensional geometry, point focus, two axis tracking). The PTC collector is generally oriented either with its axis in East-West, or North-South or polar and tracks the sun only along one axis. Various orientations, geometrical dimensions, radiative surface properties, radiative transmittance properties, etc for sophisticated model of PTC were studied in details by Edenburn(54) and then by Ramsey(55) (Experiments).

6.7 High concentration Solar Collectors

For getting concentration of 50 or above 50, the solar energy concentrations which held promise figs. (14-18) are:

1) Paraboloidal mirror; with concentration ratio in the range 500-3000 (theory developed by Bendt and Rabl(56) and also by Horton and McDermit(57).
2) The power tower, with approximate concentration in the range of 1000-3000.
3) Spherical mirror; concentration (c) = 50-150.
4) Axicon mirror with concentration of 10-80(32).

Classification of photovoltaic concentration devices is given in Table 2. Thus Table 2 gives an overview of the possible concentration designs. Except for the lowest concentration factors, tracking is always needed.

It is concluded from the above discussions that the key to producing low cost concentrator is to use low cost materials and large scale manufacturing processes. Thus to identify suitable solar energy concentrator in choosen concentration range, optimizing a vareity of conceptual designs for large scale production, selecting cost effective materials, and developing manufacturing processes, are a few concepts which, still need thorough decicated works to answer the questions, properly.

7. EXPERIMENTAL APPARATUS FOR COOLING OF PHOTOVOLTAIC CELLS AT HIGH SOLAR CONCENTRATION.

A number of constraints are associated when solar cells are used with high concentration of energy. The efficiency of solar cells, drops sharply at high levels of energy concentrations as a result of the temperature rise at the junction. Cells must be cooled to operate efficiently. For this one can use passive cooling or active cooling. Passive devices generally used large finned surfaces that are cooled by means of fluids in natural convection, whereas for active devices either running water or air-forced ventilation have been used. From experimental results conducted by group of scientists at Universita di Pisa(22), it has been concluded that active cooling gives better results, inspite of the fact that in active cooling installation costs are higher and more careful maintenance is required.

The experimental unit with heat pipe(using passive cooling concept) was developed and experimented by the Pisa's university group. The cooling device so designed together with a dual mirror system for concentrating the incoming solar energy above 50 suns is briefly described in Fig. 19.

As shown the heat pipe (a sealet tube containing a saturated vapour under working conditions) has been bolted to the concentrator, with the evaporator tied to the bottom of the cells. The pipe is heated at one end, to get the liquid vaporize whereas at the other and the vapour condenser. The two ends sections are connected adiabatically.

The design for adiabatic section is such that the fins of the condenser are nearly vertical and in the shade of the concentrator when operating conditions are the worst possible with external temperature at a maximum.

The thermal behaviour and the general criteria governing a passive system consisting of heat pipe which is a gravity assisted only and has no cepillary structure is discussed in Ref.(22). A first set of experiments was performed on a suitable prototype, whose characteristics are reported for different working fluids-water, ethyl alcohol, Freon 11, Freon 113- and in various working conditions.

Besides this the same group has also designed a new type of passive cooling device for working in full sunlight by natural convection in East-West cylindrical parabolic concentrator. As outlined by this group (Ref. 22), it is a two phase thermosymphon with Freon 11 as working fluid. The new device provides full suppression of the thermal contact resistance by immersing the cells in the cooling fluid. Moreover, this new device has been fully characterized both from the thermal and the electrical point of view. Moreover, thorough exhaustive analysis was also performed by florschuetz to give complete information regarding adequate cooling of solar cell under high concentration. A simplified model for preliminarly assessment of alternative cooling schemes was developed. Using this model the effect of both the passive and active cooling system on the performance of photo cell concentrator system was analyzed in details. The various schemes (generally employed for cooling) which were analyzed are depicted in Fig. 18.

8. TECHNIQUES FOR CHARACTERIZATION OF SOLAR CELLS

It is worth mentioning fact that a single analytical technique cannot be used to analyse various defects and inhomogenoties in detail. Therefore, a variety of techniques and meamurement set-ups are required for characterising the solar cell. The various techniques used new-a-days for the purpose stated above include :

i) I-V characteristics
ii) C.V characteristics
iii) Optical scanning
iv) Spectral Response

8.1 I-V Characteristics

The relationship between the current and voltage in an ideal p-n junction is given by

$$I_l = Io\left[\exp (Ve/KT) - 1\right]$$

Where V is the voltage imposed across the junction, e the electronic charge, K Boltzmann's constant, and T the absolute temperature. The net current is equal to the differences between normal diode current and the light generated current. The corresponding I-V curve and electron potential diagram for an ideal solar cell are given in Figs. 20-21. The open curcuit voltage Voc for the ideal cell is given by

$$Voc = (KT/e) \ln \left[(I_L/Ic) + 1) \right]$$

Where I_L = light generated current and Ic is the saturation current. The open circuit voltage of a cell usually decreases linearly with inacreasing temperature.

The point P_{max} on the I-V curve in Fig. 20 represents the maximum power point. The maximum efficiency for the coil is obtained by dividing (Imp. Vmp) by the total power density of the sunlight (P sun). In general we have

$$\eta = \frac{Imp.\ Vmp.}{Psun} = \frac{I_L.\ Eg}{e.\ Psun} \quad \frac{Imp.\ Vmp}{I_L.\ Voc} \ . \ \frac{e.\ Voc}{Eg}$$

where $\frac{Imp.\ Vmp}{I_L.\ Voc}$ = Fill factor and $\frac{e.\ Voc}{Eg}$ = voltage factor

The fill factor is a measure of the cell's series resistance, the lower the series resistance the higher the fill factor. A typical value of the fill factor for a good silicon cell is about 0.8 whereas voltage factor is about 0.5.

Thus the light I-V characteristics of a solar cell give cell efficiency, open circuit voltage, short circuit current, maximum power, series resistance, shunt resistanace, reverse saturation current, voltage factor and fill factor.

8.2 C-V Characteristics.

The voltage dependence of the junction capacitance is most commonly employed to study junction behaviour and determine junction-related parameters. C-V measurements are used to determine the junction behaviour of the cell.

8.3 Optical Scanning

Optical scanning is used to detect the defects in the cell like, localized defect, microcracks and metalization defect which are introduced due to improper handling and by thermal effect. Optical scanning is a simple technique which can give the defect map for a solar cell. Here in this technique a fine spot of a laser beam rasters the surface of the cell. The detailed abouts the electrically active defect can be have by monitoring the response photo-current (Isc) from the solar cell. The mapping can be done either on a storage oscilloscope in the Z-modulation mode or on x-y recorder in the Y-modulation mode. The Y-modulation mode is used to estimate the defect, quantitatively whereas Z-modulation provides information regarding its nature. For quantitative determination of the damage on the collection efficiency, it is necessary to evaluate the degradation of the short circuit current under constant illumination.

8.4 Spectral Response

The spectral response analysis of the solar cell is used to get information about the parameters such as quantum efficiency, collection efficiency, diffusion length of minority carriers, width of the diffused region and an estimato of the barrier height. It also provide information regarding a variety of spatial defects.

9. ECONOMIC CONSIDERATION OF PHOTOVOLTAIC CONCENTRATOR SOLAR CELL

Since for all practically useful devices, a balance between high efficiency and low cost is desirable, it is worth considering whether the association of concentration devices with solar panels would offer potential advantages, either for improving the system's performance of decreasing the cost, or both. However, it has been addressed little so far.

It has been suggested that photo cell with high efficiency, through little expensive, when used at high intensity might be an promising achievement to yield cheaper electricity. The following formula suggested by David Feiman(36) can be used for cost analysis purpose of system under consideration i.e.

$$C = \frac{C_c + RC_o}{R.\eta_c \cdot \eta_o \cdot I}$$

where C = unit cost of electricity produced
C_c = cost per unit area of photo cell
C_o = cost per unit aperture area of concentrator
I = solar power normally incident/unit area of concentrator aparture
η_c = photo cell efficiency
η_o = concentrator efficiency
R = concentration ratio

Inspection of David's relation suggests that in concentrating photovoltaic system, the cost of the generated electricity can be controlled to a larger possible extent by the cost of the concentrator rather than the cost of the solar cells which have a relatively small effect on the cost of generated electricity. The details studies regarding this aspects have also been conducted by Roy (1978)(12) and the results obtained from his theoretical model are illustrated in Fig. 22. The relationship between the cost of generated electricity by solar cells as a function of cell efficiency and collector concentration ratio is the salient feature of Fig. 22. With light concentration, the relative weight of the cell cost decreases with the increase of the concentration ratio R, even for very expensive cells. The minimum electricity cost as shown on the additional axis on the left, shifts to a region of higher concentration ratio for higher efficiency cell and also shows a lower dip in the cost curves of Fig. 22. This results from the combined effect of both high efficiency and a high concentration ratio. The example illusterate that the concentrator approach may produce electricity costs much lower even when very high cell costs are allowed for high efficiency cells.

ACKNOWLEDGMENTS

The authors would like to thank the Department of Non-Conventional Energy Sources, Government of India, for financial support during the course of this project vide sanction no. 31/112/84-PV. One of the authors (H.P.G.) would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.

Table 1 : Solar Cell Material Candidates(26)

			Major materials			
		Mobility (800°K) (cm^2-V^{-1} sec^{-1})		Lefetime (sec)		Experimental diffusion
Material	Energy gap (eV)	μ_n	μ_p	τ_n	τ_p	Length (μm)
Si	1.1	1450	500	400		100
GaAs	1.4	8500	400	50	110^{-2}	5
CdS	2.6	340	615	100	10^{-2}	∼1
S	1.5	6000	4000			
Se (Max)	1.6	2	17			
SiC(β)	2.6	1000	10			
As_2SO_s	1.6	15	45			
Sb_2O_3	1.2	15	45			
AlSb	1.6	400	400			
GaP	2.2	7 200	100			
$CdAs_2$	1.0		100			
InP	1.2	4000	>600	2000	2	
ZnSe	2.6	500	900			
CdSe	1.7	600				
CdTe	1.4	700	65			

Other materials

Material	Energy gap (eV)	Material	Energy gap (eV)
Co_2Si	1.9	Ca_2So_3	1.9
Cu_2O	2.0	In_2To_3	1.2
Cu_2S	1.8	Sb_2S_3	1.5
Cu_2Se	1.3	InN	2.5
$CdAs_2$	1.0	BSb	2.6

Table 2 Classification of Photovoltaic Concentration Devices.

Concentration factor	Optical device	Tracking	Solar cell cooling	Solar cell design
1-4	Trapezoidal groove	No	No	Conventional silicon cell
4-10	Compound concentrator	Needed for the higher concentration factors	No	Conventional silic cells with narrower collection grids.
5-100	Cylindrical or Parabolic cylindrical trough. Fresnel lenses with one-axis concentra-	Yes	Up to a factor of 50, passive cooling (fins) suffices. Above 50, active cooling (Water) is needed	Conventional silicon cells with thicker n-layer and very narrow collection grids. GaAs cells
50-5000	Paraboloidal reflector	Yes	Water cooling	Vertical multi-junction solar cell's GaAs cells.

REFERENCES

1. O' Donnell, D.T. etal, 'Performance of Silicon and Gallium Arsenide Concentration Cells', Proceedings, 13th IEEE Photovoltaic Specialists Conference, Washington, DC, June 1978.
2. J.W. Stultz and L.C. Wen, 'Low-cost silicon solar array project', Rep. 5101-31, Jet Propulsion Laboratory, Pasadena (1977).
3. D.L. Evans, 'Simplified Method for predicting photovoltaic arrays output', Solar Energy 27, 555-560(1981).
4. J.J. Loferski, 'Photovoltaic cells and increased Solar Energy Conversion Efficiency', Conf. Rec. 12th IEEE Photovoltaic Specialists Conf., Baton Rouge, Louisiana (1976).
5. J.M. Woodall and H.J. Hovel, App. Phys, Lett, Major Increase in Solar Cell Efficiency Achieved- IBM Research Highlights (1977).
6. Mitsuhiro Yamade, etal, 'Gallium Arsenide Concentrator Solar Cell' Sumitomo Electrical Technical Review, Number 22, 243-250 (1983).
7. J.R. Hanser & P.M. Dunbar, ('Performance limitations of Silicon Solar Cells', IEEE Trans, Electron Devices, 24, 305 (1977).
8. F.A. Shirland, 'The History, Design, Fabrication and Performance of Cds Thin Film Solar Cells', Advance Energy Conversion 6, 201, (1966).
9. 'Review of World Experience and Properties of Materials for Encapsulation of Terrestrial Photovoltaic Arrays', Contract E.R.O. A/J.P.L./954328-76/4 Final Report (1976).
10. Photovoltaic system Concept Study, Rep. ALO-2748-12 Spectrolab, Inc., Sylmar, CA (1977).
11. D.L. Evans and L.W. Florschuetz, 'Cost studies on Terrestrial Photovoltaic Power Systems with Sunlight Concentrator', Solar Energy 19, 255(1977).
12. A.S. Roy, 'Economic Analysis of Concentrators for Solar Cells', Solar Energy 21, 371-375(1978).
13. E.L. Ralph, 'Use of Concentrated Sunlight with Solar Cells', Solar Energy 21, 371-375(1978).
14. C.M. Garner, etal, 'High Efficiency Silicon Cells for Luminescent Solar Concentrators', Solar Cells, 4, 37-46, (1981).
15. H.A. Vander Plans, etal, 'Performance of AlGA As/GaAs Terrestrial Concentrator Solar Cells', Proceeding 13th IEEE Photovoltaic Specialists Conference, Washington, D.D., June 1978.
16. O'Donnell, D.T. etal, 'Characteristics of Solar Cells Designed for Concentrator Systems', Proceedings, American Section ISES Annual Meeting, Orlando, FL, June 1977.
17. Alvi, N.S., etal, 'The potential for increasing the Efficiency of Photovoltaic Systems by Using Multiple Cell concepts', Proceedings, 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, LA, Nov. 1976.
18. E.L. Burgess, 'Photovoltaic Energy Conversion Using Concentrated Sunlight', Optical Engineering, November 16, No. 3, May-June, 1977.
19. D. Esteve etal, 'Design of a Photovoltaic Power Array with Concentrated Sunlight', Records for the Photovoltaic Solar Energy Conference, 360-369, Luxembourg (1977).
20. P. Schoffer and W. Beckman, 'Photo voltaic Power systems Using High Solar Energy Fluxes', Final Report to U.S. Army Electronic Command, Ft. Monmouth, No. 3 on Contract DA-28-043, U. of Wisconsin Engs., Exp. Station, Madison, Dec. 1965.
21. A. Saxena, 'Degradation, study of Concentrated Silicon Solar Cell', M. Tech. Dissertation, IIT Delhi(1984).
22. C. Casnrose, etal, 'Experimental Apparatus for Cooling of Photovoltaic Cells at High Concentration', Revue Internationals D'-Heliotechnique, 2nd Semestre, 36-41, (1980).

23. M.W. Edenburn, 'Active and Passive Cooling for Concentrator Photovoltaic Arrays', (Paper delivered at the Fourteenth IEEE Photovoltaic Specialists Conference, San Diego, CA, Jan. 7-10, (1980).

24. L.W. Florschuetz, 'On Heat Rejection from Terrestrial Solar Cell Arrays with Sunlight Concentration', Work Performed under Sponsorship of the National Science Foundation, Research Applied to National Needs, as part of Grant GI-41894.

25. P. Rappaport, 'Photovoltaic effect and its utilization', Solar Energy 3(4), 8-18, (1959).

26. Charles E. Backus, 'Photovoltaic Conversion', Reprinted from Solar Energy Engineering (1977), Academic Press, Inc. London.

27. A. Rabl and Roland Winston, 'Ideal Concentrators for Finite Sources and Restricted Exit Angles', Report No. EFI 76-12, The University of Chicago, 1976.

28. R.L. Cole etal, 'Application of Compound Parabolic Concentrators to Solar Photovoltaic Conversion', Final Report, prepared for the Division of Solar Energy, U.S. Energy Research and Development Administration under contract 0-31-109 38.

29. W.S. Ittner, IIT, 'An Array of Directable Mirrors as a Photovoltaic Solar Concentrator', Solar Energy 24, 221-234, (1980).

30. K.G.T. Hollands, 'A Concentrator for Thin-Film Solar Cells', Solar Energy 13, 149-163, (1971).

31. Yukihiko Nakete etal, 'Performance of Circular Fresnel lens Photovoltaic Concentrator' Proceeding of the Ist Photovoltaic Science and Engineering Conference in Japan, 1979, Japanese Journal of Applied Physics, Vol. 19, Suppliment 19-2, 75-76, (1980).

32. U.H. Kurzweg, 'Characteristics of Axicon Concentrators for use in Photovoltaic Energy Conversion', Solar Energy 24, 411(1980).

33. Raymond J. Claxton, 'Frasnel lens-concentrating Collector', Proceedings of the E.R.D.A., Conference on Concentrating Solar Collectors, Atlants, GE. 1977.

34. L.W. James, and J.K. Williams, 'Fresnol Optics for solar Concentrator on Photovoltaic Cells', Proceeding 13th IEEE photovoltaic Specialists Conference, Washington, D. C., June 1978.

35. D.L. Evans, W.A. Facinelli and L.P. Kechier, 'Simulation and Simplified Design Studies of Photovoltaic Systems', Rep. SAND 80-70/3. Sandia Laboratories, Albuquerque(1980).

36. David Faiman, 'Concentrator Cost Bound for High Efficiency Photovoltaic Power Production', Solar Energy 22, 397(1979).

37. D.L. Evans, 'Simplified Method for Predicting Photovoltaic Array Output', Solar Energy 27, 550-560, (1981).

38. Yoshihiro Hamakaue, 'Recent Advances in Amorphous Silicon Solar Cells and their Technologies', Proceeding, Intersol, 85. Biomial Congress of the International Solar Energy Society, June 23-29, 1985.

39. R.W. Stacey and P.G. McCormick, 'Seasonal Performance of Reflector Augmented Photovoltaic Modules', Proceeding Bionnial Congress of the International Solar Energy Society, June 23-29, 1985, Canada.

40. H.Tabor, 'Mirror Boosters for Solar Collectors', Solar Energy 10, 111(1966).

41. K.C. Mannan and R.B. Bannarot(1977), 'Optical Geometries for one and two Faceted Symmetric Side-wall Booster Mirrors', Presented at Flat-plate Solar Collector Conference, Orlando, Florida, Feb., 28-March 2, 1977.

42. J.L. Russel, 'Technical Report', Gulf General Atomics Corporation, (1974).

43. J. Langerhorst, G. Prast and T. Thalhammer, 'Solar Energy', Report prepared for Ministry for Development Corporation, Netherlands(1977).

44. V.K. Barnov and G.K. Malnikov, 'Study of the Illumination Characteristics of Hollow Foccus', Soviet Journal of Optical Technology, 33, 408-411(1986).

45. H. Hinlerberger and R. Winston, 'Efficient light Coupter for the Hold Cerankov', Review of Scientific Instruments, 37, 1094-1095.

46. M. Ploke, 'Licht Fuahrungesainrichtungen nit aterhor kon zentrationswirking', Optik, 25, 31-43, (1967).

47. A. Rabl. 'Intermediate Concentration Solar Thermal Collectors' Chapter 8, Solar Energy Handbook Edited by J.E. Kreider and F. Kruither, McGraw Hill Book Co., 1981.

48. L.J. Hastings and S.A. Allums, 'Performance Characteristics of a 1.8 x 3.7m Fresnel lans Solar Concentrator' 3, Energy, 3(2), 65-68(1979).

49. D.T. Nelson, D.L. Evans and R.K. Bansa, 'Linear Fresnel lens Concentrators', Solar Energy, 17, 285-289, (1975).

50. W. Smulmayer, 'A Solar Strip Concentrator', Solar Energy, 14( ), 327-335, (1973).

51. E.M. Kritchman, A.A. Friesem and G.Y. Akutiali, 'Highly Concentrating Fresnal lenses,' Applied Optics, 18(5), 2688-2695(1979).

52. E.M. Kritchman , A.A. Friesem and G.Y. Akutiali, 'Efficient Fresenal lens for Solar Concentration', Solar Energy, 22, 119-123(1979).

53. R.M. Cooby, 'The Cylindrical Fresenl lens as a Solar Concentrator', Final Report, Ball State University-Marshall Space Flight Centre Cooperative Agreement, Muncie, Indiana, N.C.A. B-00103, Modification no. 1, June 1979.

54. M.W. Edenburn (1976), 'Performance analysis of a cylindrical parabolic focussing collector and comparison with experimental results', Solar Energy, 18, 437-444.

55. J.W. Ramsey, G.P. Gupta and G.R. Knowles, 'Experimental Evaluation of a Cylindrical Parabolic Solar Concentrator', J. Heat Transfer, Trans. ASME, 99, 163-166(1977).

56. P. Bandt and A. Rabi, 'Optical Analysis of Point Focul parabolic Radiation Concentrators' SERI/TR-331-336, 1980, Golden(Colorado), Solar Energy Research Institute and also in Applied Optics, 20(4)m 674-683, 1981.

57. T.E. Horton and J.H. McDermit, 'Optical Desing of Solar Concentrators', J. Energy, 4(1), 4-9, (1980).

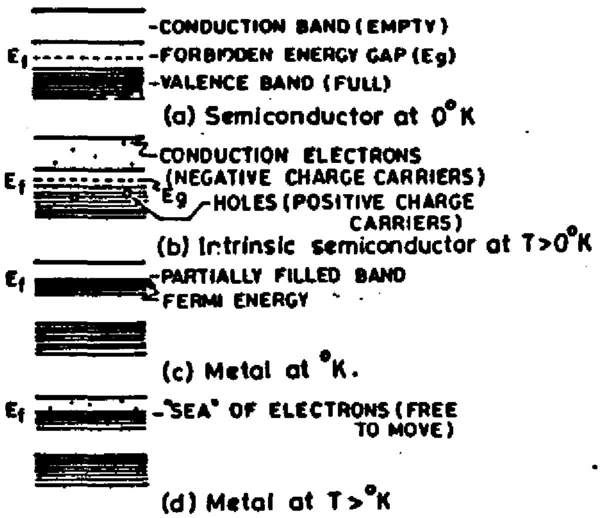


Fig. 1 One-dimensional Energy band diagrams for different types of materials suitable for solar cell (26).

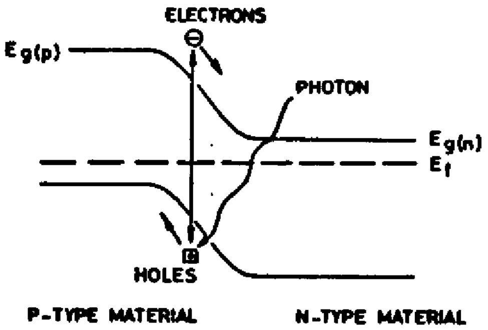


FIG. 2. THE INHERENT ELECTRIC FIELD PROVIDED BY a p-n JUNCTION [26].

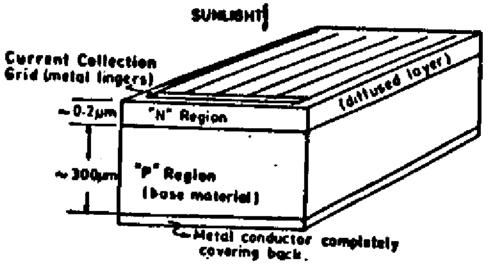


Fig.3 Physical configuration of a typical solar cell.(26)

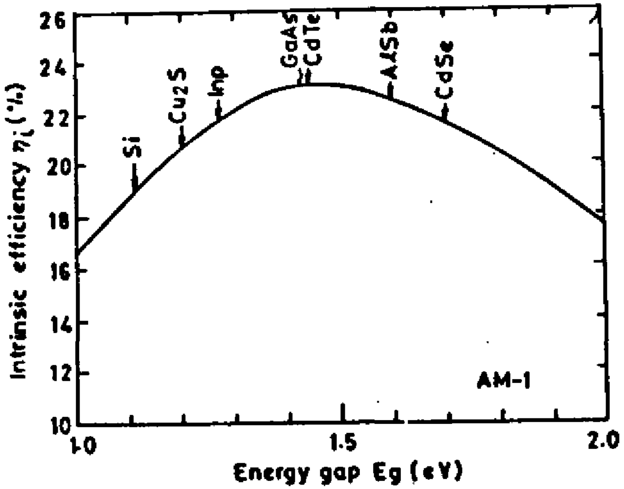


Fig. 4 Relation between intrinsic efficiency η_i and energy gap Eg of various Solar cells (6).

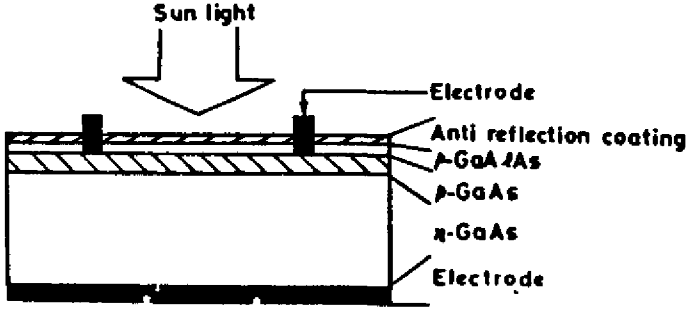


Fig. 5 Structure of GaAs solar cell with heteroface structure (6).

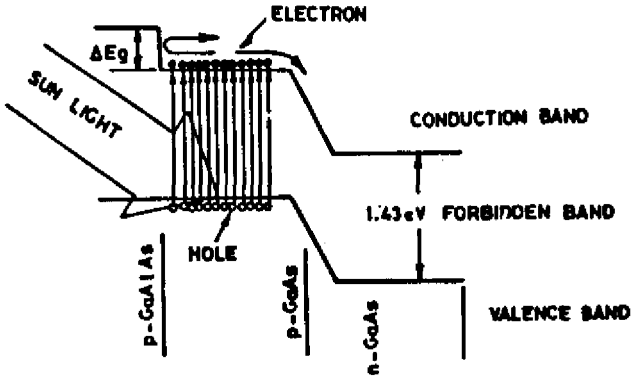


FIG.6. ENERGY BAND DIAGRAM OF GaAs SOLAR CELL WITH HETEROFACE STRUCTURE [6].

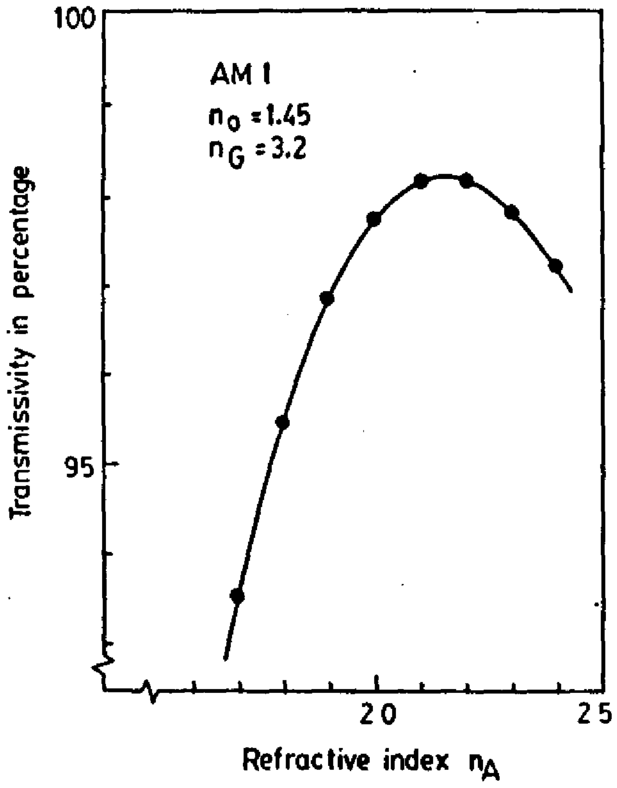


FIG.7. RELATION BETWEEN REFRACTIVE INDEX OF ANTI-REFLECTION LAYER AND TRANSMISSIVITY [6].

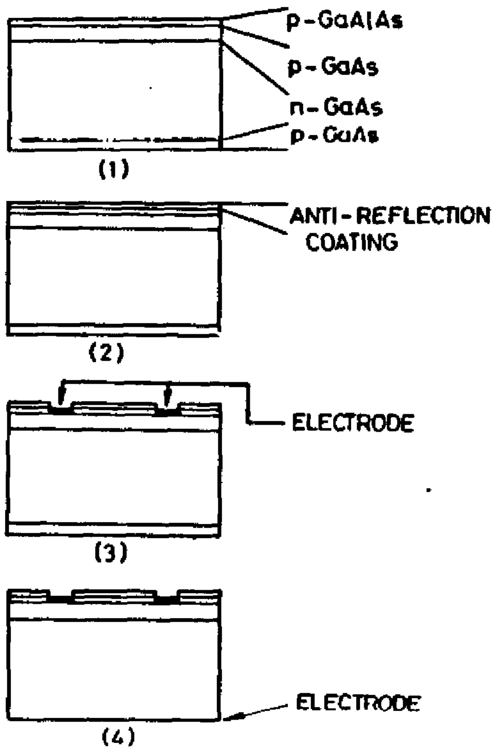


FIG.8. FABRICATION PROCESS OF SOLAR CELL [6].

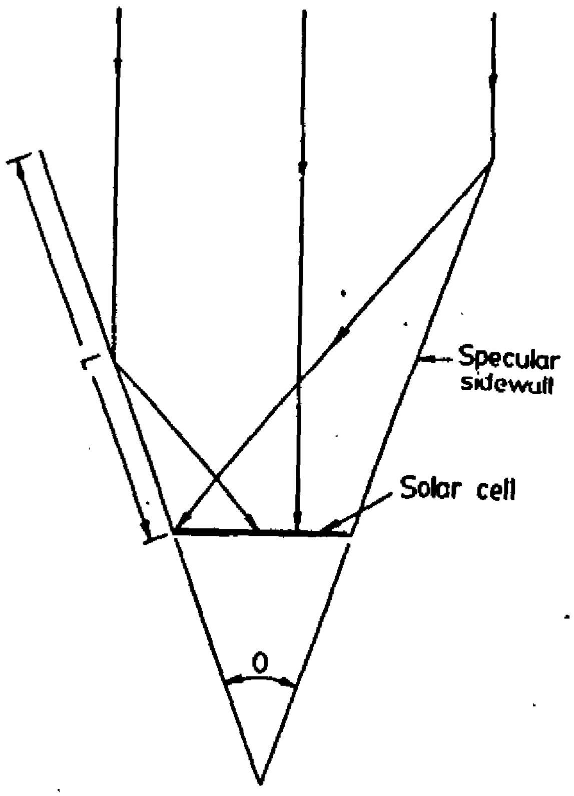


FIG. 9. A V-TROUGH CONCENTRATOR [30].

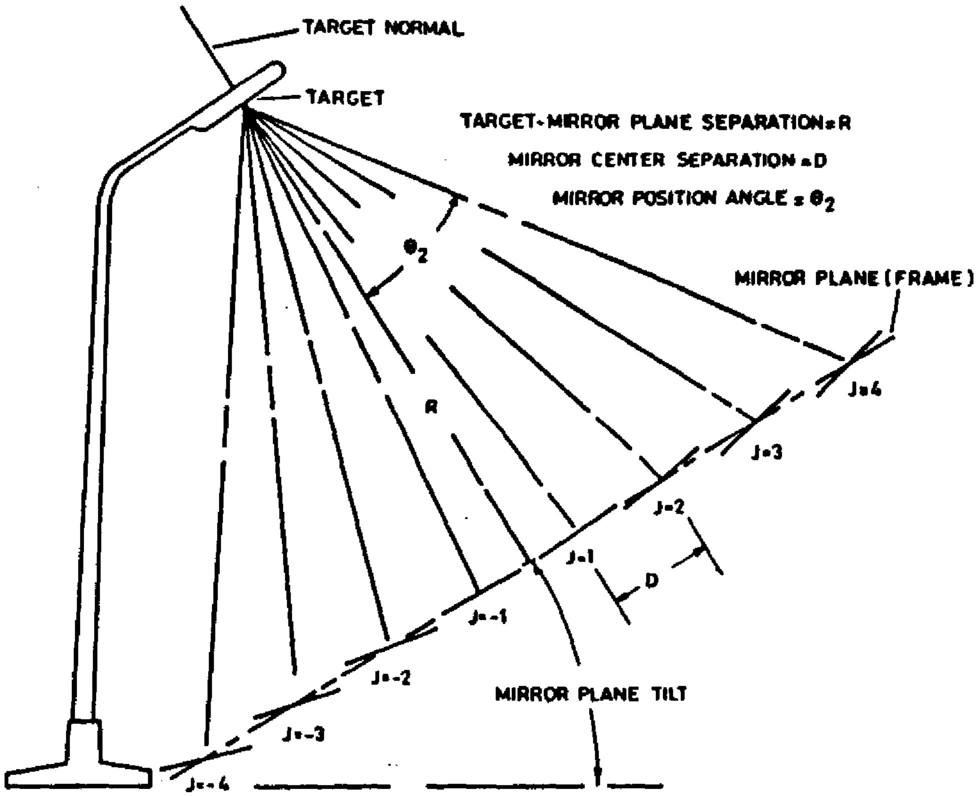


Fig. 10 Cross-section and target-mirror geometries of an Array of Directable Mirror used as Photovoltaic Solar concentrator(29).

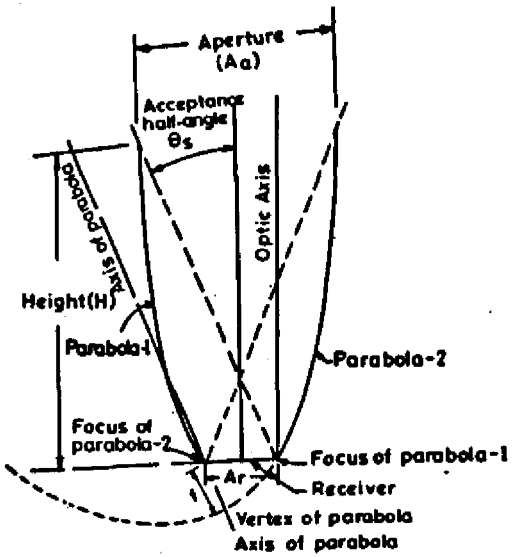


Fig. 11(a) Cross-section of a compound parabolic concentrator (44)

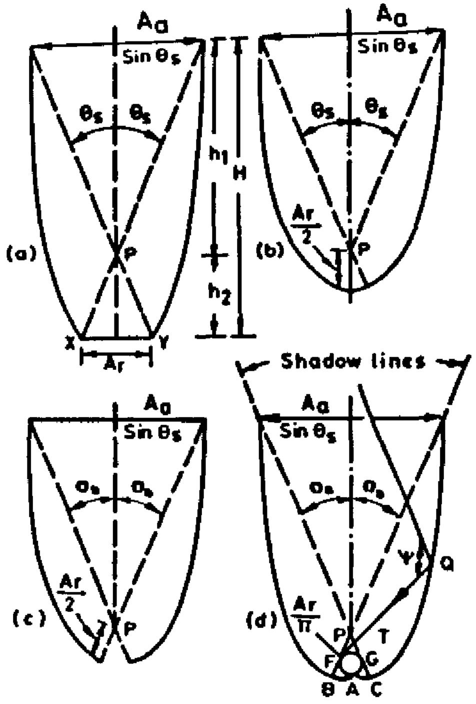


Fig. 11(b) Four CPC Collector concepts; (a) basic CPC; (b) fin receiver; (c) Wedge; and (d) tubular receiver (47).

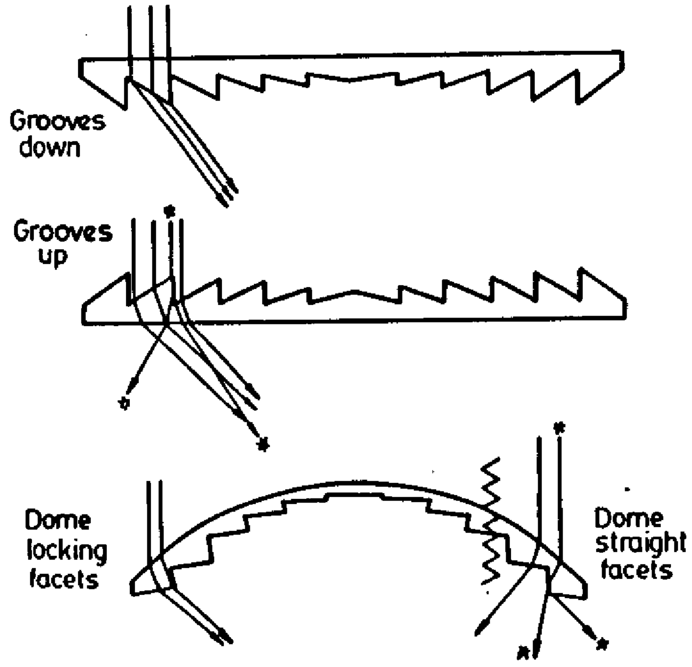
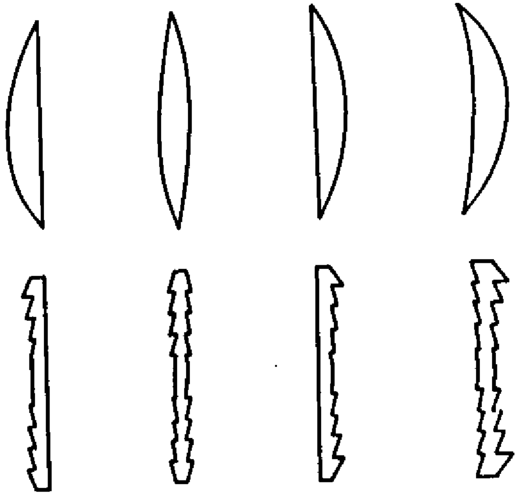


FIG.12 (a) FRESNEL LENS OF THREE DIFFERENT TYPE [34]



(I) COMPARISON OF LENS AND EQUIVALENT LENS.

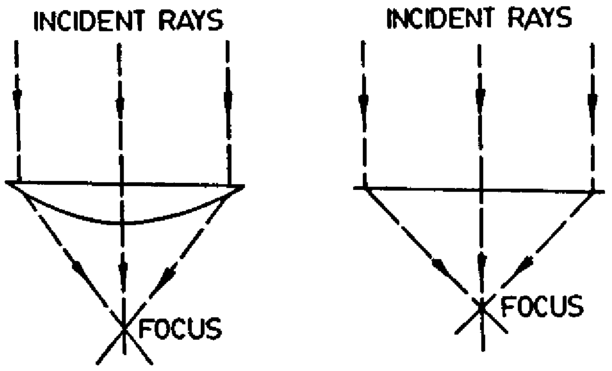


FIG.12(b). COMPARISON OF PLANE-CONVEX LENS ON EQUIVALENT FRESNEL LENS.

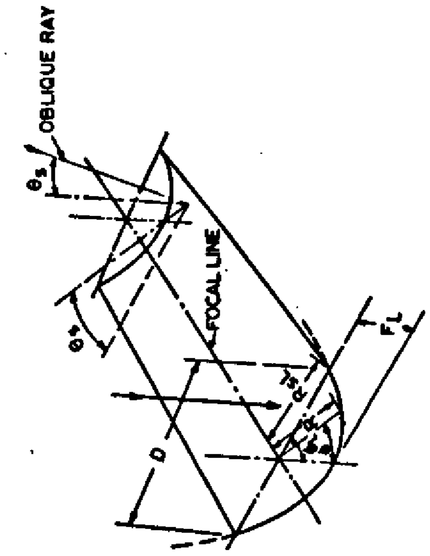


Fig.13(a) Basic geometry of a parabolic trough concentrator. (54)

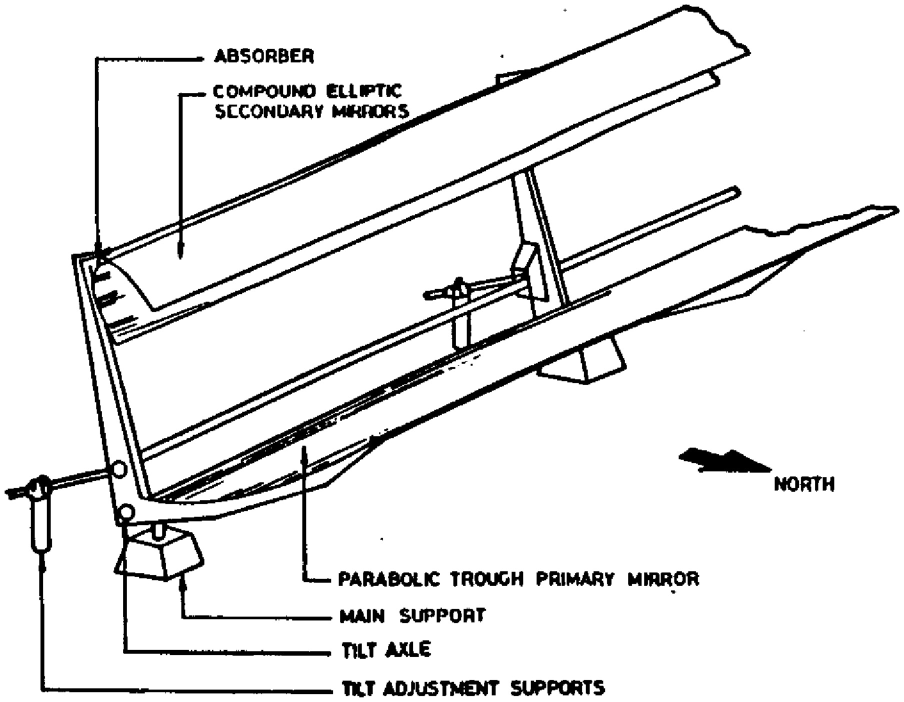
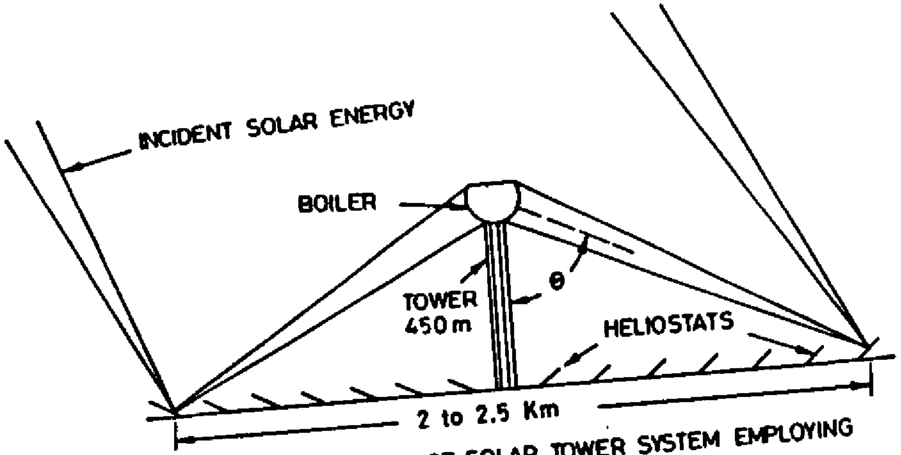
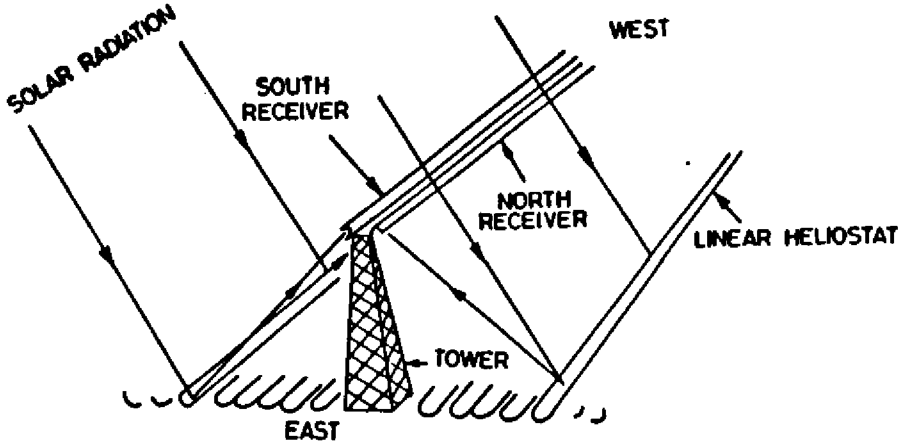


FIG.13(b) EXPERIMENTAL PARABOLIC TROUGH COMPOUND ELLIPTIC CONCENTRATOR (NON-TRACKING) shown in summer position.



(A) CROSS-SECTIONAL VIEW OF SOLAR TOWER SYSTEM EMPLOYING PLANE HELIOSTATS.



(B) CROSS-SECTIONAL VIEW OF SOLAR TOWER SYSTEM EMPLOYING LINEAR HELIOSTATS.

FIG.14. SOLAR POWER TOWER.

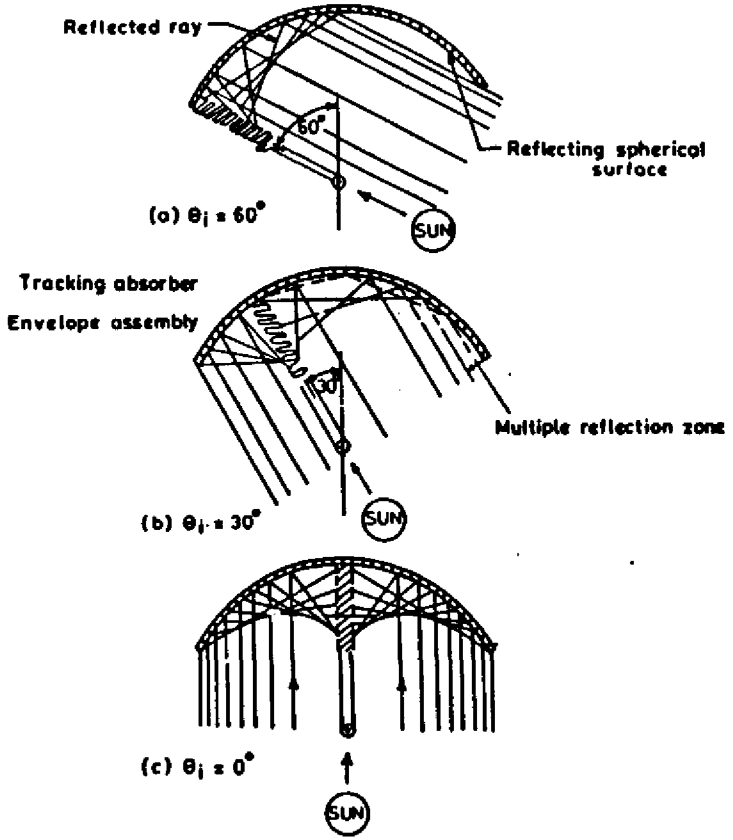


Fig. 15 Ray trace diagram for a fixed spherical concentrator for three incidence angles (58).

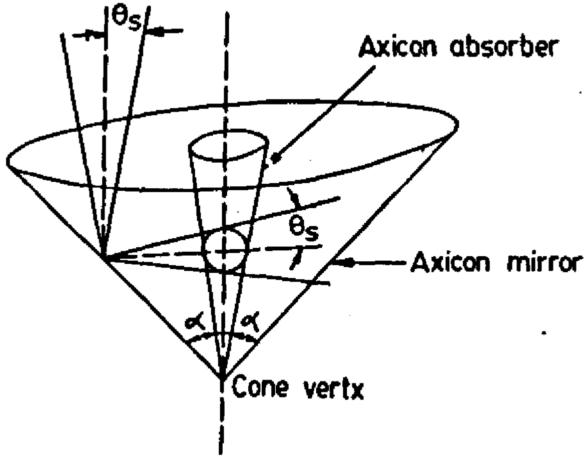


FIG.16. DIAGRAM OF AXICON MIRROR COLLECTOR WITH 90° VERTEX ANGLE.

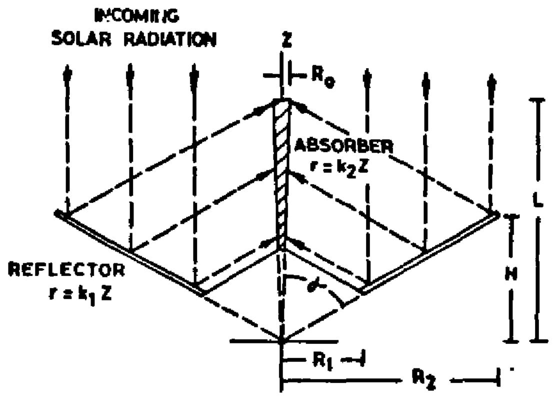


FIG.17. SCHEMATIC OF THE TRUNCATED AXICON COLLECTOR [32].

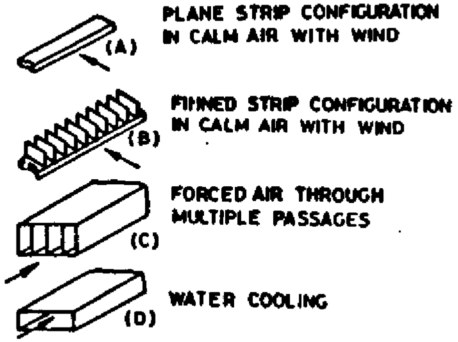


FIG.18. SCHEMATIC REPRESENTATION OF SEVERAL COOLING CONFIGURATION [24].

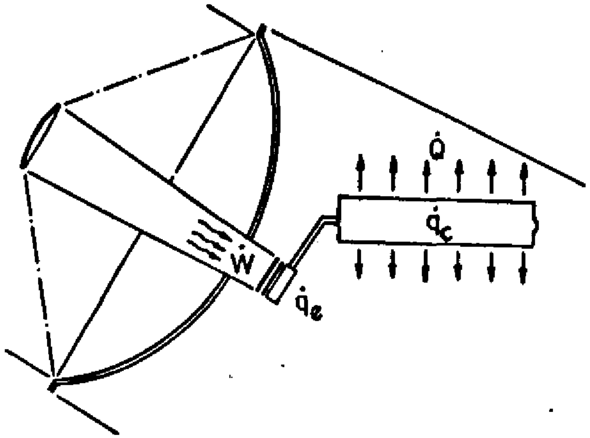


FIG.19. COOLING DEVICE (NOT TO SCALE) [22]

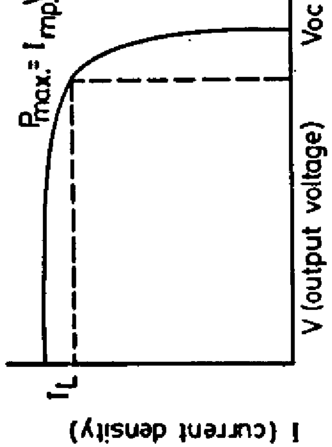


FIG.20. I-V characteristics of a ideal solar cell [26].

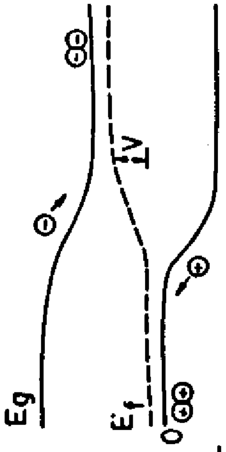


FIG.21. Energy band diagram of an ideal solar cell [26].

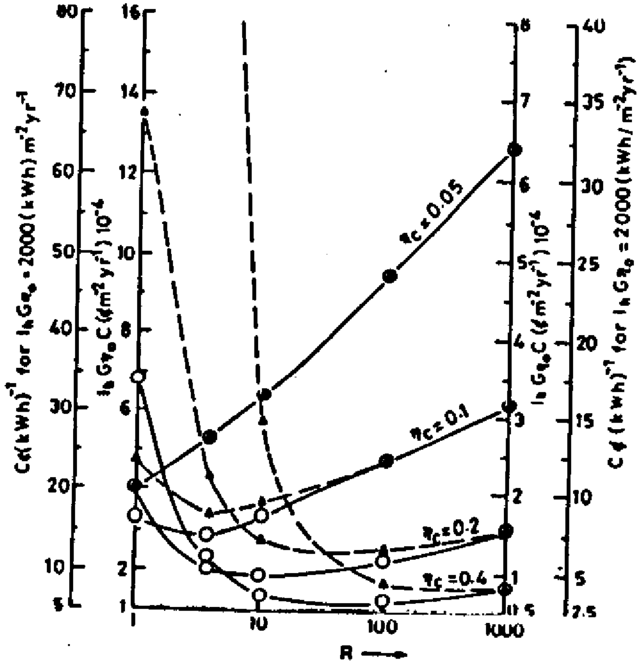


Fig. 22 Cost of generated electricity by solar cells as a function of cell efficiency and collector concentration ratio (Right-hand side vertical axes relate to collector and cell cost smaller by a factor of 2 than the left-hand vertical axes.(12)