QUASI-STATIC CONCENTRATED ARRAY WITH DOUBLE SIDE ILLUMINATED SOLAR CELLS

A. Luque, J.M. Ruíz, A. Cuevas, J. Eguren, J. Sangrador,
G. Sala, J.M. Gómez Agost, J. del Alamo

Laboratorio de Semiconductores E.T.S.I.T.
Instituto de Energía Solar
Universidad Politécnica de Madrid
Madrid-3, Spain

ABSTRACT

Double side illuminated (D.S.I.) cells placed in proper quasi-static concentrators allow for double theoretical gain than that of conventional cells.

A concentrator prototype is presented which provides Double side illumination with a practical gain of 8 and an acceptance (half gain) angle of ± 11°. This concentrator also provides cooling for the cells so that they can operate at 10°C over the ambient under an irradiance of 90 mw/cm^2 and wind velocity of 1 m/seg. Three types of D.S.I. cells are being developped. Practical efficiencies of 15,5% have been practically demonstrated.

1. INTRODUCTION

R. Winston(1) and his collaborators have developed cylindrical concentrator profiles which are able to cast all the light incident through the concentrator entrance aperture on a trough-like collector of arbitrary section, provided that the projection of the incident rays of the sun on a plane normal to the cylinder generatrix forms an angle with the mirror axis smaller than the angular acceptance ϕ_m.

The concentrator gain which is defined as the ratio of the concentrator aperture length A_E to the collector perimeter P_C is given by

$$C = \frac{A_E}{P_C} = \frac{n}{\sin \phi_m} \qquad (1)$$

where n is the index of refraction of the medium in which the collector is immersed.

A. Rabl. has demonstrated that this relationship constitutes a thermodynamical optimum (2). This type of concentrator has been used for photovoltaic concentration by placing a solar cell of conventional (3) or special (4)(5) shape as the collector in the concentrator bottom and placing the collector in a E-W orientation, facing the South with some elevation angle close to the local latitude.

High values of the angle ϕ_m are required to allow for changes in the sun declination throughout the year. Seasonal adjustments of the concentrator elevation angle permit smaller ϕ_m angles and allow for an increased concentrator gain.

Since the use of concentration in photovoltaic applications is intended to reduce the mass of high cost semiconductor material, the use of solar cells with maximum perimeter-to-volume ratio is required to join high gain with wide acceptance angle which insures an acceptable degree of quasi-stationarity.

The Double Side Illuminated(D.S.I.) solar cells are the shape that maximizes the ratio perimeter-to-volume. The perimeter of such a cell doubles its width; a photovoltaic concentration can now be defined as

$$C_F = \frac{A_E}{W} = \frac{2}{\sin \phi_m} \qquad (2)$$

valid only for D.S.I. cells.

A Program of Research to develop D.S.I. cells and static concentrators funded by the Spanish Assessing Committee for the Scientific and Technical Research, is currently underway at the Laboratorio de Semiconductores of the Universidad Politécnica de Madrid.

2. CONCENTRATOR

Fig. 1 shows a schematic of our present concentrator for double sided illumination based on an application of the ideas of Winston (1) to a double sided solar cell.

The first stage is a transformer of angles (6) which cast over the second stage, with an angular acceptance of ± 62°, all the light entering through its entrance aperture with an angle of ± 11,5°. The second stage is a water filled Winston mirror for double sided illumination of a vertical fin placed in its bottom (which is the D.S.I. solar cell). This second stage has an acceptance angle of ± 62°. Such

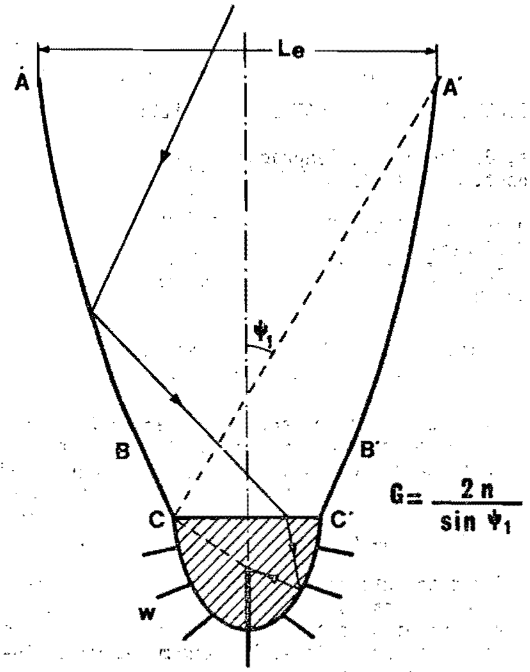

Fig. 1. A two stage static selfrefrigerating concentrator for double side illuminated cells.

a combination of concentrators is optimum in the sense of Rabl.

Our prototype is designed for 2,5 cm wide cells and has been truncated at the 63% of the theoretical height. The actual size is 75,5 cm high and 31 cm of entrance aperture. The first stage is silvered tempered curved glass. The second stage is an aluminum body covered with Al metallized mylar.

Using water as a dielectric the heat can be removed from the cell by natural convection and transported to the concentrator walls, from where it is removed by convection to the air so that the cells can be kept at low temperature to be more efficient. Despite the fact that water is the cheapest and more efficient heat remover dielectric, other dielectrics could be used to decrease the corrosion problems if a proper encapsulation cannot be used.

The use of water as a dielectric in the concentrator has several additional effects. A first effect is a reduction of the reflection of the light between the air and the cell. For normal incidence this reflection reduction produces an experimental increase of shortcircuit current of 18% after immersing the cell in the water. This effect is reduced in cells with antirreflection coating and depends on the coating characteristics.

A second effect is the absorption of the light by the dielectric which reduces the light incident in the cell. For the solar spectrum AM1 this absorption follows the experimental curve

$$\frac{I_{sc}\,(x)}{I_{sc}\,(o)} = \exp\,(-\,0{,}0192\;x) \qquad (3)$$

where I_{sc} (x) is the shortcircuit current of a cell immersed in deionized water at a depth of x centimeters.

The use of a two stage concentrator is intended to reduce the optical path of the light in the dielectric. Althought this path will be minimum if the exit angle of the first stage is 90°, a smaller angle has been selected to avoid reflection of very obliquous angles at the air-dielectric interface.

The gain of the concentrator has been measured vs. the light incidence elevation angle for zero azimuth taking into account only the direct radiation; the result appears in Fig. 2. A maximum gain of 8.01 has been obtained with an acceptance angle of ± 11,5° (50% Gain). A computer ray tracing has also been done and it has been concluded that the major reduction of efficiency is caused by the light absorption in the water while the major influence on the acceptance angle lies in the accuracy of the first stage concentrator profiles.

The thermal study of the concentrator has been done inside the Laboratory to keep under control the environmental variables. A resistor was placed in the position of the cells. This resistor was made with a two sided printed circuit plate of the same size of the cells in which a resistance with a value of a 4 Ω was etched. This resistance was supplied with a low voltage a-c current to avoid the electrolytic decomposition of the water. The objective of this resistor is to provide a power similar to the solar power concentrated on the cell.

An axial flow fan of 1500 r.p.m. and with a diameter for its rotor of 35 cm was placed at different distances from the concentrator. The speed of the wind was measured with an anemometer. Equilibrium water temperatures for different wind velocities and power are represented in Fig.3. The dynamics of the system shows that the final temperature is reached according to the equation:

$$T(t) - T_i = (T_f - T_i)(1 - \exp - \frac{t}{\tau}) \qquad (4)$$

where T(t) is the actual value of the temperature, T_i is the initial temperature and T_f the final temperature. The result of this work shows that the time constant τ is 53.4 min for the system without wind 16.4 min

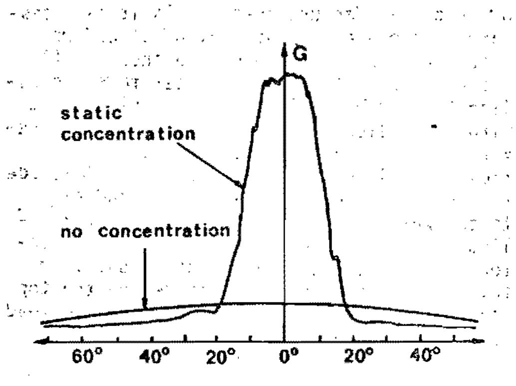

Fig. 2. Energy on the cells in the static concentrator vs. the elevation angle (zero azimuth).

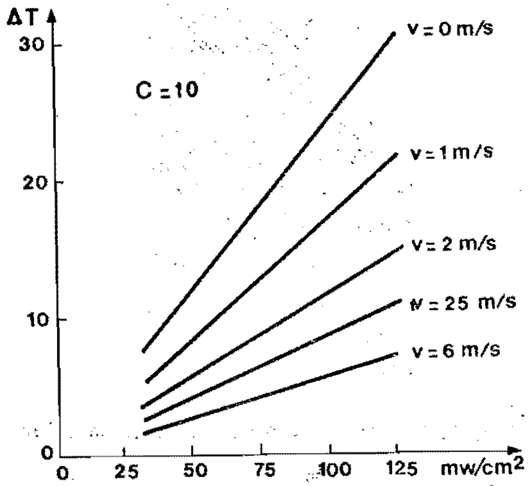

Fig. 3. Increase of water temperature in the concentrator vs. the incident power for several wind speeds.

for a wind of 2.5 m/sec. It was observed that the orientation of the concentrator had little influence on these parameters.

3. DOUBLE SIDE ILLUMINATED SOLAR CELLS

Three types of D.S.I. cells are now under development. The first one is a n^+pn^+ structure which is shown in Fig. 4. In this structure both sides are photovoltaically active. These cells have a very good carrier collection efficiency which is due to the presence of two junctions near the two surfaces of the cell. Carriers generated by long wavelength photons of the light entering by one side can be efficiently collected by the junction which is near the surface of the other side of the cell.

The shortcircuit current of this structure, even when illuminated on one side, is higher

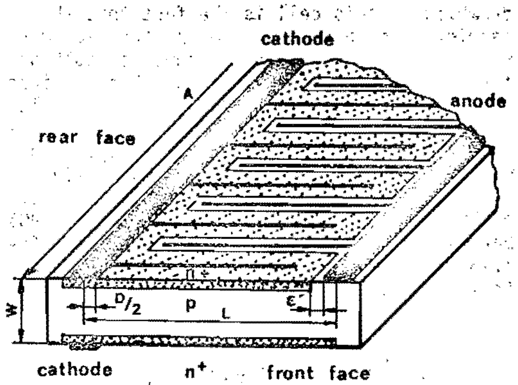

Fig. 4. The Transcell: a n^+pn^+ double side illuminated solar cell.

than that of conventional or B.S.F. cell of similar characteristics, as has been theoretically (7) and experimentally (8) demonstrated. The opencircuit voltage is also increased (9) with respect to that of conventional cells since recombination in both surfaces is reduced by the high carrier concentration near them.

In experimental 0,5 Ω cm base structures, which are appropriate from an efficiency viewpoint, the increase of the shortcircuit current due to back collection is about 8%. The increase of opencircuit voltage at one sun due to the two junctions interaction effect is of about 5 mV. The interaction between junctions can be higher for higher base resistivity cells. Due to this interaction we call transcell (TR cell) this n^+pn^+ D.S.I. cell.

Higher series resistance is expected in this cell because of the way that majority carriers have to travel along the base to reach the p contacts. Nevertheless, optimized metallization (10) patterns give experimental (8) curve factors of 0.80 wich involve cells of efficiency up to 15,5% as shown in Fig. 3. At the present stage these cells involve expensive photolithographic manufacturing processes.

In order to avoid this drawback, a second type of solar cell with a n^+pp^+ structure, as presented in Fig. 6, is also under research. The basic idea of this structure is based on the properties of the "high low" or homopolar junction pp^+ behaviour (11),(12),(13). In this junction the minority carriers are eficienty reflected towards the region of low conductivity. As it can be observed in Fig. 5 metallic grids are placed on both faces of the n^+pp^+ cell. The minority carriers generated by the light near the p^+p junction are reflected by this homopolar junction and travel by diffusion towards the pn^+ junction where they are collected. The possibility of this structure was first suggested by us (8) and has been recently (14) demonstrated. The main drawback of this cell is the fact that the carriers generated near the pp^+ junction have to traverse the entire semiconductor bulk before reaching the n^+p junction. This requires fairly large diffusion length for the minority carriers and very thin cells. We have developed techniques, similar to those suggested by J. Lindmayer (15), which permit easily handled cells 50 μm thick. With this type of cells it is possible to obtain a ratio of 90% between the integrated internal quantum efficiency for the back (n^+) side and the front (n^+) side illumination.

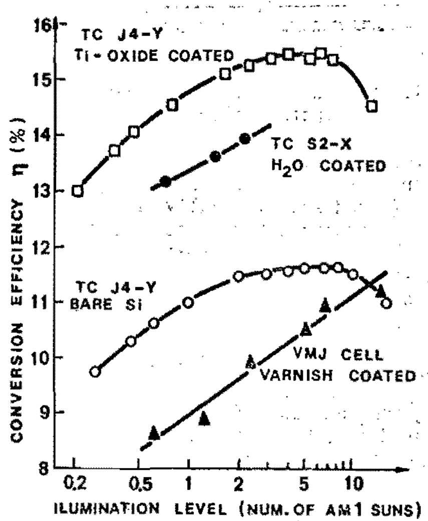

Fig. 5. Efficiency vs illumination level of transcell (TC) and multijunction (VMJ) cells.

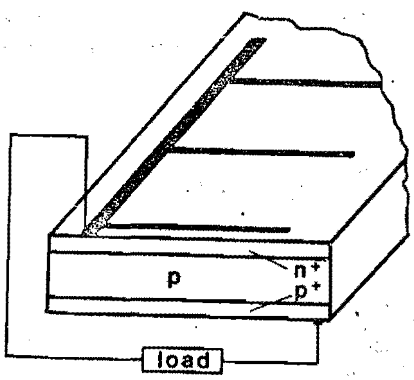

Fig. 6. The double sided surface field cell: a n^+pp^+ cell structure.

A third type of cells which is now under development in our Laboratory was first proposed for high concentration cells by scientists of NASA Le.R.C. (16). These cells are inherently double-sided so that they can be used in connection with our concentrators. In order to manufacture these cells it is necessary to prepare conventional n^+pp^+ wafers which are then piled up with a sheet of Al placed between the wafers. After that the piling is heated to alloy the aluminium sheet with the silicon. In this way a series of several (16 to 50) diodes are connected in series. The piling is now cut with a multiblade sawing machine in a direction perpendicular to the wafers so that thin slices of the piling of n^+pp^+ diodes are obtained as presented in Fig. 7. These slices are about 1 mm thick. A layer of Ni is deposited on the top and bottom of the piling and a soft tin-lead solder is the deposited.

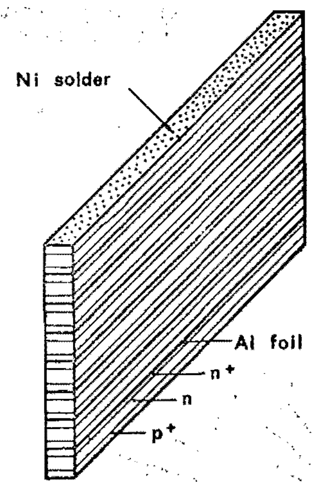

Fig. 7. The double sided multijunction solar cell.

The main theoretical advantage of the structure is its low series resistance because there is no lateral flow of majority carriers to reach the contacts. The main drawback lies in the fact that the ratio of illuminated area to junction area is small. This produces a low value of the opencircuit voltage per cell. The performance of this cell is presented in Fig. 3. Important improvements on these performances can be expected from a refinement of the technology. The process to manufacture this cell is quite cheap: there is a disadvantage in the fact that the sawing procedure we have mentioned wastes a high amount of silicon. While the transcell can use a low grade silicon the last two cells have to use a long lifetime, high quality silicon.

4. COST ANNALYSIS

The expression for the cost of a photovoltaic array is

$$Y = (C_p + X\delta/G)/1000\eta$$

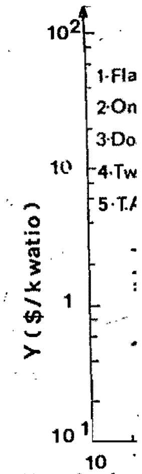

Fig. 8. Arr
rer

where Y is
the concent
lar cells
which take
the cell c
the concen
In Fig. 8
tems have
that the d
be the mos
cells cost
the array
appears th
tion.

Concentrat
system
Flat pane
Quasi-Stat
single fac
Quasi-Stat
double fac
Tracking
Concentra
Beam spli
Concentra

5. CONCLU

A novel s
being dev
de illumi
ting conc

Practical
tance ang
Under con
of 1 m/se
water tem
the conce

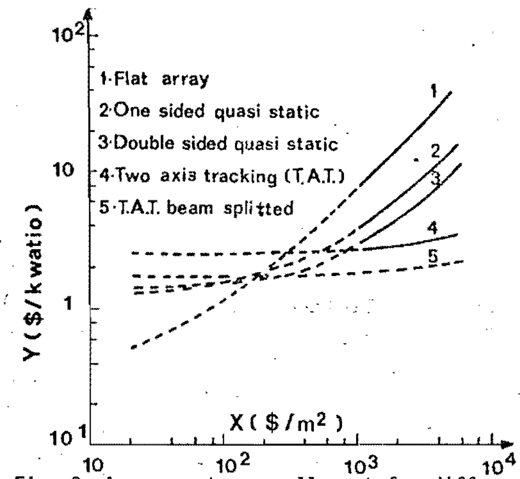

Fig. 8. Array cost vs. cell cost for different types of concentration.

where Y is the generator cost in \$/PW, C_p is the concentrator cost in $\$/m^2$, X is the solar cells cost in $\$/m^2$, δ is a coefficient which takes into account the influence of the cell complexity in the cell cost, G is the concentration gain and η the efficiency. In Fig. 8 several types of concentration systems have been analyzed. It can be concluded that the double sided static concentrator can be the most attractive solution for solar cells costs of about 200 $\$/m^2$. In this case the array will be of 1,2 \$/PW. In table I appears the parameters used for this evaluation.

Table I

Concentration system	G	C_p	δ	η %	Marked with
Flat panel	1	50	1,0	14	1
Quasi-Static single face	4	130	1,0	10	2
Quasi-Static double face	8	130	1,3	10	3
Tracking Concentrator	60	300	1,2	12	4
Beam splitted Concentrator	500	500	15,0	30	5

5. CONCLUSION

A novel system of static concentration is being developed . This system uses double side illuminated solar cells and self refrigerating concentrators.

Practical concentrator gains of 8 with acceptance angles of ± 11,5° have been obtained. Under condition of 90 mW/cm^2 and wind speed of 1 m/sec this concentration will produce a water temperature of 9°C over the ambient in the concentrator and probably about 1°C more for the cell, depending on the encapsulation.

Double side illuminated cells are being developed with three different procedures, and efficiencies of 15,5% have been obtained for one of them; the variability of the others has been demonstrated.

This concentrator system can reduce the cost of the photovoltaic power plants without the drawbacks of maintenance existing with tracking concentrators.

6. ACKNOWLEDGMENT

The first stage of tempered glass concentrators was manufactured by Cristaleria Española, S.A. under our drawings.

7. REFERENCES

(1) Winston R. and Hinterberger H. Solar Energy, 17, 255 (1975).
(2) Rabl. A. Solar Energy, 18, 93 (1976).
(3) Goodman N.B., Ignatius, Wharton L. and Winston R. Applied Optics, 15, 2434 (1976).
(4) Mlavski A., Stormont R.W., Taylor A.S. 12th Photovoltaic Specialists Conference Baton Rouge (1976).
(5) Jhonson G.R., Miller M.G., and Tanner D.P. Records of the E.C. 1977 Photovoltaic Solar Energy Conference. Luxembourg 259 (1977).
(6) Rabl A. and Winston R. Applied Optics, 15, 2880 (1976).
(7) Luque A., Cuevas A., Eguren J., Ruíz J. M., and Gómez J.M. Records of the E.C. 1977 Photovoltaic Solar Energy Conference, Luxembourg, 269, (1977).
(8) Luque A., Cuevas A., Eguren J. Solid State Electronics, 21, 793, (1978).
(9) Cuevas A., Sangrador J., Luque A., Ruíz J.M., Sala G. 1979 Photovoltaic Solar Energy Conference; West Berlin (1979).
(10) Luque A. Informe Técnico UPM/ETSIT/LS/1278.
(11) Mandelkorn J., and Lamnek J.H. Records of the 9th IEEE Photovoltaic Specialists Conference, 66, (1972).
(12) Godlewski M.P., Baraona P.R., and Bradhorst H.W. Records of the 10th IEEE Photovoltaic Specialists Conference, 40, (1973).
(13) Fossum J. IEEE Trans. Electron Dev., ED-24, 322, (1977).
(14) Luque A., Eguren J., Alamo J. Internal Quantum Efficiency of back illuminated npp+ cells. ESSDERC 78, Montpellier (Sept 1978).
(15) Lindmayer. Records of the 1977 E.C. Photovoltaic Solar Energy Conference, 76, (1977).
(16) Sater L., Brandhorst H.W., Rily T.J. and Hart R.E. Record of the 10th IEEE Photovoltaic Specialists Conference, 188 (1973).