IC/87/247
INTERNAL REPORT
(Limited distribution)

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

SILICON SOLAR CELL TECHNOLOGY STATE OF THE ART AND A PROPOSED DOUBLE SIDED CELL *

Mohamed M. Seddik **
International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

A review of the silicon technology state of the art is given. It had been found that single crystal silicon efficiency was limited to $\geq 20\%$. The reason was identified to be due to the recombination current loss mechanisms. However, use of new technologies such as back-surface field, surface passivation, double anti-reflection coatings and back-surface illumination demonstrated to achieve higher efficiencies. Experiments were carried out to evaluate the effect of back surfaces illumination on the cell efficiency enhancement. It was found that for single cell, back-surface illumination contribute a 12% increase in efficiency whereas for double cell illumination (back-to-back cells) the improvement was 59% increase in efficiency. A V-shaped flat mirror reflector with optimum angle of 45° to the plane of the cell from both sides achieved the ultimate efficiency performance. Finally, a proposed high current - high efficiency solar cell called "Double Drift - Double Sided Illumination Cell" was presented. The new structures were in the form of $n^{+}pn^{+}$ or $p^{+}np^{+}$ double junctions. The expected efficiency ranges 50-60% with proper material design, double anti-reflection coatings and V-shaped irregular plane mirror reflector illumination.

MIRAMARE - TRIESTE
August 1987

* To appear in the Proceedings of the Workshop on "Materials Science and the Physics of Non-Conventional Energy Sources" , ICTP, Trieste, 26 August-18 September 1987.

** Permanent address: Engineering Physics Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

1. Introduction

The photovoltaic effect in which generation of voltage due to absorption of sunlight has been observed in 1876 by Adams and Day. They observed the photovoltaic in selenium structure and also the spectral sensitivity of the selenium photoconductors . However, the first solar cell fabricated from silicon materials as a pn-junction was demonstrated by Chapin et al [1] at the Bell Telephone Laboratory in 1954 in which they reported an efficiency of 6% . Independently, in the same year another research group;Reynolds et al [2] at the U.S.Air-Force Aerospace Research Laboratory observed the photovoltaic effect at rectifying contacts to cadmium sulfide single crystal . The first major application of the silicon solar cells appeared in the space programme of 1958 in U.S.A.,where the first space craft launched " Vanguard I" which was powered by solar cells.

Since then, a great and substantial progress has been made in developing pn-junction solar cells in countries like U S A,USSR,Japan,England,France,Germany,........etc . Presently,all satellites used in communications arround the world are powered by photovoltaic solar cell systems. The advantage of photovoltaic energy over that of the conventional energy sources may be briefly stated as:

1- Solar cells directly convert the sunlight into electricity without any intermediate thermal process which makes it a clean and nonpolluted source.
2- Maintance free, durable and reliable systems.
3- Suitable to be used in isolated and remote areas.

On the other hand,solar cells suffer from some disadvantages such as:

1- High cost of solar cells makes the terrestrial applications uneconomical compared to the conventional power , specially if the demand of the power is large.
2- For no-sun conditions,the solar systems requires an electric storage which still forms a problem for large scale applications .
3- Conversion efficiencies achieved to date are still limited to less than 20% .

Despite of these disadvantages,it is conceivable that the years of hard work of many researchers covering the full range of photovoltaic technologies such as analsis,desgin , processing,testing and development of manufactures processes would achieve high efficient-low cost solar systems. It is to be noted that the technological steps taken since the historical energy crisis of 1973 to the present time,resulted in price reductions more than an order of magnitude .

2. Silicon Technology

All modern energy technologies have developed in parallel with substantial studies and inventions in material science. For instance,the first usable solar cell was only made possible by the extensive practical and theoretical advances in silicon technology . Yet,more than thirty years have already passed with many attempts to reduce the cost of the solar cells to the desired goal of U.S.$ 0.5 W_p^{-1} but the cost still high due to the expensive fabrication techniques used . These techniques are :

The Standard Process of growing single crystal silicon from molten silicon is called Czochrolski process in which silicon wafers are manufactured in industry . Whereas,polycrystalline silicon is produced by Casting process which results in the production of multiple grain silicon instead of a single crystal as in the czochrolski process . It should be noted that casting techniques result in cheaper silicon wafers but with very large silicon crystals . The material in the casting process although it is produced at lower cost than single crystal but it has lower conversion efficiency due to the effect of grain boundries in the materials .

The difficulty of reducing the prices of the above mentioned techniques lies in developing an appropriate sheap slicing technique to minimize the damage produced in the process . The solution to this problem is to develop a process to go directly from molten silicon to sheet or ribbon silicon . Presently,growth rate of ribbon silicon technology exceeds 30 cm^2/min. of 0.1 millimeter thicknesses which results in cell efficiencies of 17-18% [3] . The projected cost for silicon ribbon technology is shown in Tables 1 and 2 . Table 1. illustrates the predictions of different technical parameters of the photovoltaic solar cells production during the period of 1985-1990. These parameters include growth rate,encapsulated-cell efficiency,module efficiency and silicon cost . Table 2. shows a comparison of State of the art ribbon technology with the projected cost/peak watt.

Amorphous silicon is prepared by using Thin Film Technology in which silcon is deposited onto a glass substrate,quartz, or stainless steel sheets . Over 15 years of investigation for many promising materials and by using thin film technology to date none of these materials have resulted in stable commercially low cost solar cells . Table 3. Shows a recent summery of developments in amorphous silicon solar cells [4]. A fairly large number of firms in U.S.A. and Japan have extensive research work on Si:H(silicon hydrogenated) solar cells and achieve efficiencies up to 12.7% as shown in table 3 . Various cell structures have been investigated;namely, double and triple-stacked junctions as well as modules and heterojunctions .

At the present stage in the development of photovoltaic technology,one can say that single crystal silicon is the most efficient,the most promising material for solar cell fabrication to date .

3. Single Crystal Silicon State Of The Art

The ultimate performance of the conventional single crystal silicon solar cells (e.g. air mass 1,1 sun: AM1) appear to be limited in efficiency to 20% . Jet Propulsion Laboratory [5] has reported that 17% (AM1) cells are in production . Table 4. summerizes the performance of four high efficiency silicon solar cells and compared the results with ideal cell theory[6-9] . The experimental results given in table 5 , illustrate the variation in the material parameters such as resistivity (ρ) , lifetime (τ) , diffusion length (L_n) and base recombination velocity (S_B) . The conclusion drawn from the results shown in table 5 is that base recombination losses are the main limiting factors to the 20% efficiency values in the single crystal silicon solar cells . Further improvement in the cell efficiency would require to reduce the recombination losses .

The Passivated Emitter Solar Cell (PESC) structure has been responsible for recent improvements in silicon solar cell performance[10] . The effect of substrate resistivity upon the PESC cell performance has been resulted in even further improvement in the cell efficiencies. These are shown in table 5 in which efficiencies up to 19.6% have been achieved .

An optimum double layer of anti-reflecting(AR) coating on oxide-passivated cells provides an improvement over single AR-coated cell resulting in cell efficiencies approach to $\geqslant$20% was reported by Arohatgi and Choudhury [11] . The limiting efficiency of silicon solar cells under concentrated sunlight has been studied by Campbell & Green [12] . They reported that the limiting efficiency lies in the 36-37% range regardless of concentration ratio compared to the limiting value of 29.8% for non-concentrating cell with isotropic response . The techniques uses the back side point-contact configuration have been extended to result in 27.5% efficiency at 10 W/cm^2 (100 suns, 24 °C) making them one of the most efficient solar cell to date [13] . The improvements reported are largely due to the incorporation of optical light trapping to enhance the absorption near bandgap light.

The recent improvement in the performance of silicon single crystal solar cells has produced outstanding energy conversion efficiency of 27.5% by the use of high resistivity rear contacted cells [14] . Parallel improvements in the more conventional bifacially contacted low-resistivity cell are described,also,which have increased the efficiencies of such devices to 25% in 50-100 suns concentration range .

Several authors [15-18] have been investigating , modeling,designing and observing the cell transiets in recent months . A progress is made in high efficient cells (18.5%) by using ion implantation for small area silicon single crystal solar cells in an attempt towards developing a flat plate module with efficiency exceeding 17% . A detailed comparison of various approaches to cell design was made and module test data for these designs were represented 19 . The latest results published were for a singl crystal p^+nn^+ silicon solar cells with efficiencies of 19.5% . The cells have been fabricated using the technique of glow-discharge implantation and pulsed excimer laser annealing together with techniques for reducing the recombination current 20 .

Some results [5-14,19-24] which are representative of the present state of the art are given in Fig. 1. It should be pointed out that the results of fig. 1 are laboratory results obtained from exceptionally the best research groups working in the field of solar cells technology.

Fig. 1 shows that the efficiency of the single crystal silicon solar cell (AM1) is limited to $\geqslant$ 20% efficiency. However, passivated and concentrated cells achieve higher efficiencies between 27.5 -29.5% .

Now, the question is :

Why single crystal silicon solar cells have limited efficiency of $\geqslant$20% ?

To answer this question,understanding of the device physics is essential to show the limitations currently been observed in the cell design .

4. Characterizing Equations

The standard governing equations used to model the steady state carrier transport in silicon solar cells are given as :

a) The continuity equations for holes and electrons

$$\vec{\nabla}.\vec{J}_p = - q (R - G) \quad (1)$$

$$\vec{\nabla}.\vec{J}_n = q (R - G) \quad (2)$$

where the hole and electron current densities are

$$\vec{J}_p = - q \mu_p . p \vec{\nabla} V_i - q D_p \vec{\nabla} p \quad (3)$$

$$\vec{J}_n = - q \mu_n . n \vec{\nabla} V_i - q D_n \vec{\nabla} n \quad (4)$$

b) The Poisson's equation.

$$\nabla^2 V_i = - \frac{q}{\varepsilon} (p + N_D - n - N_A - N_T) \quad (5)$$

c) The carrier density equations.

$$p = n_i e^{q(\varphi_p - V_i)/KT} \quad (6)$$

$$n = n_i e^{q(V_i - \varphi_n)/KT} \quad (7)$$

where G = photogeneration rate per unit volume;
R = net recombination rate per unit volume;
μ_p, μ_n = mobilities of holes and electrons;
D_p, D_n = hole and electron diffusivities;
N_D, N_A = Donor and Acceptor concentrations;
N_T = number of charges trapped at the recombination centers ;
φ_p, φ_n = hole and electron quasi-Fermi levels;
V_i = potential at the intrinsic level;
ε = dielectric constant; and
q = electronic charge.

$\bar{J}_p$ and $\bar{J}_n$ could be eliminated from equations 1-4 and the resulting equations along with equation 5 represent three non-linear differential equations in three unknowns V_i , p and n . It is very important to incorporate N_T and to consider $i_p = - i_n$ in the steady state solution .
The three equations with given appropriate boundary conditions could be solved using computer programing. Many cell design calculations have been reported in the literature [25-29] . The terminal current (I) is then given as (after [30,31])

$$I = q\int_v G\,dv - q\int_v R\,dv - \int_s J_p.\hat{n}\,ds - \int_{s2} J_p.\hat{n}\,ds - \int_{s1} J_n.\hat{n}\,ds \qquad (8)$$

Or

$$I = I_{ph} - I_{b,rec.} - I_{s,rec.} - I_{cont,rec.} \qquad (9)$$

where I_{ph} = the photogeneration current;

$I_{b,rec.}$ = bulk recombination current;

$I_{s,rec.}$ = surface recombination current;and

$I_{cont,rec.}$ = contact recombination current .

The terminal voltage is given as

$$V = \frac{KT}{q} \ln \left(\frac{pn}{n_i^2} \right) - V_{res.} \qquad (10)$$

Note that $\int_v$ and $\int_s$ represent the volume and surface integrals, $\hat{n}$ represents a unit vector and $V_{res.}$ represents the resistive potential loss due to the metal grid .

A typical current - voltage characteristics of a solar cell is shown in fig. 2 in which curve(a) shows the characteristics of the junction when it is not illuminated and curve (b) when it is illuminated .

The behaviour of the solar cell is characterized by four parameters, the short-circuit current I_{sc}, the open-circuit voltage V_{oc}, the efficiency at the maximum load power point EFF and the fill factor at the maximum load power point FF , which are given as follow :

$$I_{sc} = I_o \left[\exp\left(\frac{q\,V_{oc}}{K\,T}\right) - 1 \right] \qquad (11)$$

$$FF = \frac{I_{max}\,V_{max}}{I_{sc}\,V_{oc}} \qquad (12)$$

$$EFF = \frac{P_{max}}{P_{in}} = \frac{I_{max}\,V_{max}}{P_{in}} \qquad (13)$$

The maximum efficiency is given as

$$EFF = \frac{FF.\,I_{sc}.V_{oc}}{P_{in}} = \left(\frac{I_{sc}}{P_{in}} \right) FF.V_{oc} = 0.36\ FF.V_{oc} \qquad (14)$$

where I_o is the dark current .

A simplified solar cell equivalent circuit is shown in fig. 3 in which R_L is the load resistance, R_s is the series resistance and R_{sh} is the shunt resistance .
The ideal current for solar cell characteristics can be described by

$$I = I_L - I_o \left[\exp\left(\frac{V - IR_s}{K\,T}\right) - 1 \right] \qquad (15)$$

Where I is the current flowing into the external circuit from the solar cell power source and V is the terminal voltage of the cell . It should be noted that the series resistance has a serious effect on the cell efficiency and should be reduced by proper design of metalization .

Reffering back to equation 9 , it is seen that the recombination currents represents the main loss mechanisms in high efficiency single crystal silicon solar cells . The base recombination at residual defect and impurity recombination centers is identified to be the cause of the 20% efficiency barrier published to-date . To break this barrier, residual base recombination losses must be eliminated and emitter recombination must be reduced . Proper design of the emitter dopant concentration profile can minimize or approximatly eliminate the emitter recombinations [32] . It remains the base recombination which represents the intrinsic losses that cannot be reduced due to the interband recombination mechanisms .

It remains, however, a need for substantial improvements to achieve high efficiency single crystal solar cells and to overcome the recombination problem by material quality, purity and improved design considerations. It is also important to use new technologies such as the back surface field(BSF), surface passivation, efficient double layer-anti reflection coating, reduced heavy doping, reduced contact recombination and back-surface reflectors to achieve ultimate efficiency performance .

In the next section experimental results of the back surface illumination and their effect on the efficiency performance will be given . Illuminated back-to-back solar cells will be tested and results will be discussed . A new solar cell structure " double drift – double sided illumination " will be presented .

5- Experimental Results and Discussion

Two n^+pp^+ – silicon solar cells supplied by Sargent-Welch Corporation of Canada were employed in this investegation . The area of each is 2 cm x 2 cm . In order to make clear how the illumination of the back surface of the cell contribute to the increase in efficiency , the following measurements were carried out :

5.1- Solar Cell Measurements

The solar cells were tested using a tungsten light source calibrated at 100 mW/cm^2 to obtain the solar parameters V_{oc}, J_{sc}, FF , and EFF . The following steps were excuted .

Step 1.1 :

The characteristics of the two cells separately were obtained . Direct solar radiations were used on the front surface with its back covered .

Step 1.2 :

The back of the cells were exposed to the reflected radiations from the ground and the front surface to the direct radiations.

Step 1.3 :

The back of the cells were illuminated by a flat mirror reflectors with the front surface illuminated directly by the sun radiations.

Summary of the results obtained in the above steps are given in table 6 .

Now, the measurements were carried out with the two silicon solar cells fastened back-to-back (i.e, n^+pp^+/p^+pn^+) and the contact leads of the p^+- regions were connected together . This connection was a parallel connection and then the following steps were excuted :

Step 2.1 : The front cell 1 was illuminated by direct sun radiations while the back cell 2 was exposed to diffuse radiations from the ground .

Step 2.2 : The front cell 1 was illuminated directly from solar radiations and the back cell 2 was exposed to reflected light from a flat mirror . Measurements were repeated several times to change the reflector positions to have the highest current reading .

Step 2.3 : Both cells were illuminated simultaneously by reflected radiations from flat mirrors . Adjustments of the mirrors position yields an optimum setting; namely a V- shaped in which the plane of the cell makes 45^o with each side of the V-shaped mirror as shown in fig.4 . It is clearly demonstrated in table 7 the effect of using two cells back to back with out introducing any reflectors and the diffued radiations from the ground were collected by cell 2, an increase of the efficiency by 12% was achieved . Using one reflector to cell 2 only demonstrated to have an increase in efficiency by 33% . The third case illustrated the highest contribution to the efficiency with ultimate performance of 59% increase in efficiency.

5.2- A Proposed New Solar Cell Structure

Several double drift diodes were proposed by Seddik and Haddad [33] where various device structures were analyzed and proved to deliver high power and efficiency . A review of the technology of multiple solar cells including Schottky barrier [34,35] ,hetero – junction [36,37] , pin/pin cascade [38–42] and n^+npp^+ [43] solar cells have demonstrated high conversion efficiency . These solar cells consist of multiple layers semiconductors arranged electrically and optically in series which represent a high voltage solar cells .

In this paper I propose a new cell structure called

" Double Drift – Double Sided Illumination " solar cell. The device is either n^+pn^+ or p^+np^+ which represents a double junction cells connected in parallel back-to-back to deliver high currents . The efficiency with double sided illumination would reach up to 50-60%. The advantages of the new structures proposed here are :

1- High current devices .

2- High efficiency (expected efficiency up to 60%)

3- Simple structures to fabricate by conventional diffusion methods . Diffusion masks are not needed since the double sided of the wafer would be diffused to make the n^+ or p^+ regions and then the contact windows are etched through the SiO_2 anti-reflecting layers .

It should be noted here that the higher efficiencies could be achieved by using double anti-reflecting layers as well as irregular flat V-shaped mirror reflectors .

6- Conclusion

State of the art of the silicon tecnology was reviewed.The efficiency of the single crystal silicon solar cells were found to be limited to $\gtrsim$20% . It had been shown in the literatures that the base recombination at residual defect and impurity recombination centers was identified to be the cause of the 20% efficiency barrier . To break this barrier,recombination losses must be reduced . New technologies such as passivation, back surface field,double anti-reflection coatings and back surface illumination enhance the solar cell efficiency .

Experiments to measure the J_{sc} , V_{oc}, FF and Eff % for solar cells illuminated at the back separatly or simultaneous were performed. Increase in the efficiency by 12% , 33% and 59% had been achieved . A new V-shaped reflectors were used to optimise for the highest efficiency performances . A proposed high current high efficiency " Double Drift – Double Sided Illumination " solar cell of the forms n^+pn^+ and p^+np^+ to achieve up to 60% efficiencies were presented .

ACKNOWLEDGMENTS

The author would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.

References

1 D.M.Chapin, C.S. Fuller and G.L. Pearson, J. Appl.Phys., 25 (1954) 676 .

2 D. C. Reynolds , G. M. Leiss, L. L. Antes and R.E. Marburger, Phys. Rev., 96 (1954) 533 .

3 P. K. Henry, Proceedings of the JPL 21st Integration Meeting, Pasadena,California (1983) .

4 Y. Hamakawa ,Solar Cell Techology- ASSETT ,7(2),23-27, (1985)

5 J. B. Milstein and C. R. Osterwald,High efficiency solar cell program : some recent results, 23rd Project Integration Meeting, March 14-15,(1984); Jet Propulsion Laboratory Publ. 84-47, (1984), pp. 151-157.

6 M. A. Green, A. W. Blakers, J. Shi, E. M. Keller and S. R. Wenhan, IEEE Trans. Electron Devices, 31, (1984), 679 .

7 M. B. Spitzer, S.P. Tobin and C. J. Keavney, IEEE Trans. Electron Devices , 31 (1984) 546

8 A. Rohatgi and P. R. Choudhury, IEEE Trans. Electron Devices, 31 (1984) ,596 .

9 ASEC Applied Solar Energy Corporation ,solar cells reported in refs. 5 and 8 .

10 M. A. Green, A. W. Blakers, S. Narayanan and M. Taouk, Solar Cells , 17 (1986) 75-83 .

11 A. Rohatgi and P. Rai-Choudhury, IEEE Trans. Electron Devices, 33 (1986) 1-7 .

12 P. Campbell and M.A. Green, IEEE Trans. Electron Devices 33 (1986) 234-239 .

13 R. A. Sinton,J. Y. Gan and R. M. Swanson, IEEE Electron Device Letters , 7 (1986) 567-569 .

14 M. A. Green,Z. Jianhua, A. W. Blakers, M. Taouk and S. Narayanan, IEEE Electron Device Letters , 7 (1986) 583-585 .

15 M. E. Nell and A. M. Barnett, IEEE Trans. Electron Devices, 34 (1987) 257-265 .

16 H. Iida, T. Mishuku, A. Ito and Y. Hayashi, IEEE Trans. Electron Devices , 34 (1987) 271 - 276 .

17 F. A. Lindholm, J. J. Liou, A. Neugroshel and T.W.Tung, IEEE Trans. Electron Devices ,34 (1987) 277 - 285 .

18 D. S. H. Chan and J. C. H. Phang, IEEE Trans. Electron Devices , 34 (1987) 286 - 293 .

19 A. R. Mokashi, T. Daud and R. H. Kachare, Solar Cells , 19 (1987) 9 - 17 .

20 R. F. Wood, R. D. Westbrook and G. E.Jr. Jellison , IEEE Electron Device Letters , 8 (1987) 249 - 251 .

21 C. T. Sah, A. Fredrik and F. A. Lindholm, J. Appl. Phys., 55(4) , (1984),1174 - 1182 .

22 V. Schlosser , IEEE Trans. On Electron Devices , 31 , (1984) 610 - 613 .

23 R. H. Swanson, S. K. Beckwith, R. A. Crane, W. D. Eades, Y. H. Kwark, R. A. Sinton and S. E. Swirhun, IEEE Trans. On Electron Devices, 31, (1984) 661 - 664 .

24 B. B. Rao, S. Banerjee, W. A. Aderson and M. K. Han , IEEE Trans. On Electron Devices , 32 ,(1985) 817-821 .

25 C. T. Sah,P. C. H. Chan,C. K. Wang,R. L. Sah,K. A. Yamakawa and R. Lutwack, IEEE Trans. On Electron Devices , 28 (1981) 305 .

26 C. T. Sah,K. A. Yamakawa and R. Lutwack, Solid State Electron.,25 (1982) 851 .

27 C. T. Sah,K. A. Yamakawa and R. Lutwack, J.Appl. Phys., 53 (1982) 3278 .

28 C. T. Sah,K. A. Yamakawa and R. Lutwack, IEEE Trans. On Electron Devices , 29 (1982) 903 .

29 C. T. Sah, Solid State Electron.,25 (1982) 960 .

30 R. M. Swanson , Solar Cells , 17 (1986) 85 - 118 .

31 P. A. Basore, Proc. 17th IEEE Photovoltaic Specialists Conf. , Kissimmee, Florida, May 1-4, 1984, IEEE , New York, 1984 , p.637 .

32 C. T. Sah, Solar Cells , 17 (1986) 1-27 .

33 M. M. Seddik and G. I. Haddad, IEEE Trans. On Electron Devices , 21 (1974) 809 .

34 R. J. Stirn and Y.C.M.Yeh, Appl.Phys.Lett.,27(1976) 150.

35 T. I. Chappell, IEEE Trans. On Electron Devices, 26 (1979) 1091 .

36 W. D. Johnston,Jr. and W. M. Callahan, Appl. Phys. Lett., 28 (1976) 150 .

37 M. Bettini,K.J.Bachman, E.Buehler, J.L.Shay and S. J.Wagner, J. Appl. Phys., 48 (1977) 1603 .

38 M. F. Lamorte and D. H. Abbott,Solid State Electron., 22 (1979) 467 .

39 M. F. Lamorte and D. H. Abbott, IEEE Trans. On Electron Devices, 27 (1980) 321.

40 J. J. Hanak, Sol. Energy, 23 (1979) 145 .

41 J. J. Hanak, Proceedings of the 14th IEEE Photovoltaic Specialists Conference, San Diego, CA, 1980 (IEEE , New York , 1980 , p.623 .

42 E. K. Murray and R. M. Warner, Jr. ,J.Appl.Phys., 52 (1981) 6352 .

43 S. Hinckley , J. F. McCann and D. Haneman, Solar Cells , 17 (1986) 317 - 342 .

Table 1 Comparison of State-of-the-Art Ribbon Technology (Scaled Up) with Projections of Ribbon Technology

	Scaled-up State-of-the-Art	Intermediate Projection (Late 1980s)	Long-Term Projection (Early 1990s)
Factory size, MW/yr	25	25	25
Year of production	1985	1988	1990
Ribbon type	Dendritic web	Dendritic web	Dendritic web
Silicon cost, 1980 $/kg	55	14	14
Web growth rate, cm^2/min	10	25	35
Growth machines/operator	6	18	18
Encapsulated-cell efficiency, %	12.3	13.5	15
Packing factor	0.92	0.92	0.92
Module efficiency, %	11.3	12.4	13.8
Cumulative cell process yield	0.77	0.93	0.93

Table 2 Comparison of State-of-the-Art Ribbon Technology (Scaled Up) with Projections of Ribbon Technology (1980$/Wp)

	Scaled-up State-of-the-Art	Intermediate Projection (Late 1980s)	Long-Term Projection (Early 1990s)
Sheet growth (incl. silicon)	1.61	0.21	0.14
Cell processing	0.27	0.22	0.19
Module assembly (incl. encap. matl.)	0.18	0.16	0.15
FOB factory dock module price			
(1980 $/Wp)	2.06	0.59	0.48
(1980 $/$m^2$)	233	73.3	66.2

Table 3 Recent summary of developments in a-Silicon solar cells

Type	Configuration	Area (cm^2)	Eff. (%)	V_{oc} (V)	I_{sc} (mA/cm^2)	FF	Year	Institute
SJ	ITO/nipn a-Si/p poly Si/Al	0.082	12.7	1.380	14.18	0.65	1984	Sumitomo
SJ	ITO/nipn a-Si/p poly Si/Al	0.44	12.5	1.325	14.2	0.66	1982	Osaka Univ.
HJ	Ag/ni a-Si/P a-SiC/ text. TCO.glass	1.0	11.5	0.869	18.9	0.70	1984	Sanyo
HJ	Me/ni a-Si/p a-SiC/ text.SnO_2/ITO/glass	1.05	11.6	0.850	18.7	0.732	1985	TDK-SEL
TJ	ITO/nipnipn a-SiGe/ p a-Si/stainless steel	1.0	11.2	-	-		1985	ECD
HJ	Me/ni a-Si/p a-Sic/ TCO/glass	1.0	11.1	0.864	17.6	0.73	1984	Fuji
HJ	Ag/ni a-Si/p a-Sic/ text. SnO_2/glass	1.0	11.0	0.860	21.5	0.6	1985	Kanegafuchi
HJ	Me/ni a-Si/p a-Sic/ text. TCO/glass	0.32	10.7	0.840	18.8	0.68	1984	Komatsu
HJ	Ag/ITO/ni a-Si/p a-Sic/MTC	0.045	10.2	0.802	22.32	0.57	1984	ETL & Taiyo
HJ	Al/ni a-Si/p a-Sic/ text. SnO_2/glass	4.15	10.2	0.865	16.1	0.73	1984	ARCO
HJ	Ag/ni a-Si/p a-SiC/ SnO_2/glass	1.09	10.1	0.840	17.8	0.676	1982	RCA
HJ	Ag/p a-SiC/in a-Si/	0.084	9.6	0.848	17.1	0.664	1984	TIT
TJ	ITO/nipnipn a-Si/i a-SiGe/ p a-Si/stainless steel	0.09	8.5	2.200	6.74	0.57	1982	Mitsubishi
Mod	Me/ni a-Si/p a-SiC/TCO/ glass	100	6.1	11.96	15.6	0.61	1984	Sanyo
HJ	Me/ni a-Si/p a-SiC/TCO/ glass	100	8.0	0.850	14.4	0.654	1984	Fuji
SJ	Al/nipni a-Si/p a-SiC/ SnO_2/glass	4.15	7.7	1.710	6.23	0.71	1984	ARCO
HJ	Al/ni a-Si/p a-SiC/ SnO_2/glass	1.0	7.7	0.880	14.1	0.62	1982	Osaka Univ.
Mod	Al/ni a-Si/p a-SiC/ SnO_2/glass	400	7.5	47.8	114 mA	0.55	1985	Kanegafuchi
Mod	Me/ni a-Si/p a-SiC/ SnO_2/glass	600	7.0	16.0	12.5	0.63	1984	Sumitomo
Mod	Me/ni a-Si/p a-SiC/ SnO_2/glass	3200	6.7	48.7	890 mA	0.50	1985	Kanegafuchi

SJ: Double-stacked junction. HJ: Hetero-junction TJ: Triple-stacked junction Mod: Module

TABLE 4

Performance of four highest efficiency silicon solar cells and comparison with ideal diode cell theory

Cell type	ρ (Ω cm)	*Thick-ness* (μm)	L_B (μm)	τ (μs)	J_1 (A)	J_{sc} (mA)	V_{oc} (mV)	*FF*	*AM1 EFF* (%)	S_B (cm s^{-1})
M/I/N/P										
Ideal theory	0.2		170		3.2×10^{-13}	36.0	660	0.840	20.0	850
	0.2		170		6.6×10^{-13}	36.0	641	0.835	19.3	1750
Exp.[a]	0.2	280		20	3.2×10^{-13}	36.0	653	0.811	19.1	
$n^+/p/p^+$										
Ideal theory	0.3			13	1.2×10^{-12}	36.2	627	0.834	18.9	1100
Exp.[b]	0.3	380	150			36.2	622	0.801	18.0	
						35.9	627	0.800	18.1	
$n^+/p/p^+$										
Ideal theory	4.0			23	2.0×10^{-12}	36.2	605	0.830	18.2	650
Exp.[c]	4.0	150	263		2.0×10^{-12}	36.2	605	0.786	17.2	
	0.2					36.0	627	0.800	18.1	
n^+/p										
Ideal theory	0.15				1.0×10^{-13}	36.0	628	0.834	18.9	2200
Exp.[d]	0.15					36.0	625	0.805	18.1	
	10.0					36.5	610	0.775	17.2	

[a] Green *et al.* [6], University of New South Wales, Australia.
[b] Spitzer *et al.* [7], Spire Corporation, Bedford, MA, U.S.A.
[c] Rohatgi *et al.* [8], Westinghouse R&D Center, Pittsburgh, PA, U.S.A.
[d] ASEC [5 ,9], Applied Solar Energy Corporation, City of Industry, CA, U.S.A.

TABLE 5

Characteristics of baseline PESC cells as a function of the float zone substrate resistivity

Cell no.	*Resistivity* (Ω cm)	V_{oc} (mV)	J_{sc} (mA cm^{-2})	*FF* (%)	*EFF* (%)
M55f	0.5	629	36.9	80.4	18.7
M56ff	0.5	630	37.0	80.2	18.7
D46e	0.25	649	36.8	81.4	19.4
D46ee	0.25	649	37.0	82.2	19.8
M41p	0.20	662	36.5	81.9	19.8
M41pp	0.20	660	36.1	82.4	19.6

	Steps	J_{sc} (mA/cm^2)	V_{oc}(mV)	FF	EFF (%)
Cell 1	1.1	32.7	564	0.729	13.4
	1.2	33.8	564	0.730	13.86
	1.3	36.6	564	0.730	15.0
Cell2	1.1	32.2	572	0.737	13.6
	1.2	33.3	572	0.737	14.0
	1.3	36.0	572	0.737	15.2

Table 6. Summary of the back surface illumination for separate solar cells .

The results of the above measurements are tabulated in table 7.

	Step	J_{sc}(mA/cm^2)	I_{sc}(mA)	V_{oc}(mV)	EFF(%)
Cells	2.1	32.7	130.8	564	13.4
		4.2	16.8	492	
1&2		36.9	146.6	567	15.0
1	2.2	32.7	130.8	564	
2		10.7	42.8	552	
1&2		43.4	173.6	566	17.8
1	2.3	25.9	103.6	564	
2		26.0	104.0	572	
1&2		51.9	207.6	566	21.3

Table 7. Comparison of the performances of the solar cells when connected in parallel .

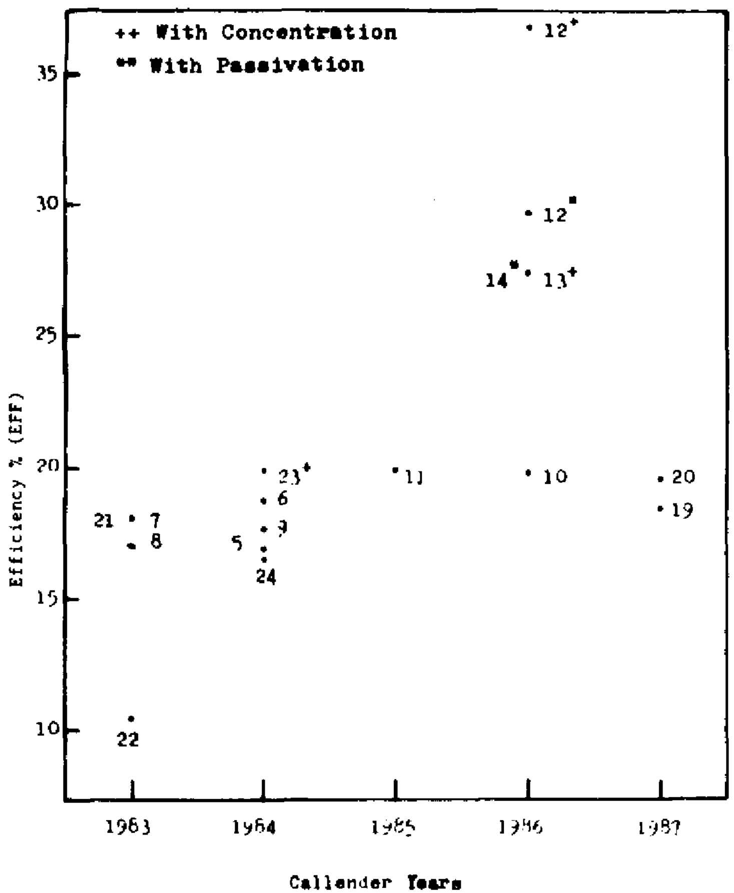

Fig. 1 State Of The Art Of The Singl Crystal Silicon Soler Cell Technology .(Reference Numbers Are Indicated)

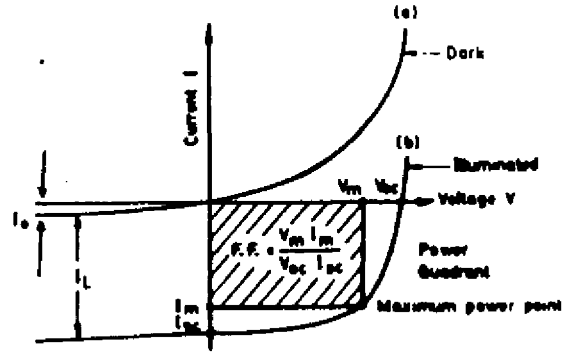

Fig.2 Typical current-volatage characteristics of a solar cell.

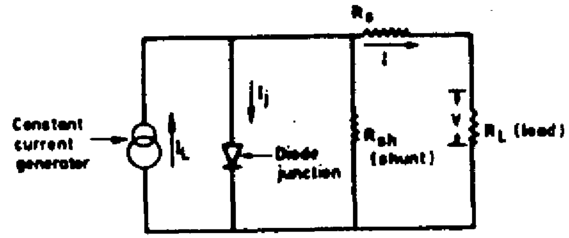

Fig.3 Equivalent circuit of a solar cell.

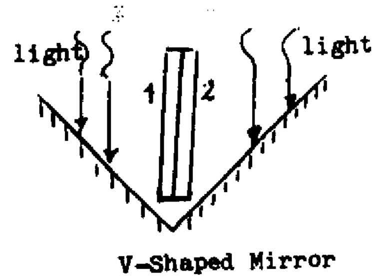

Fig.4 Illumination of the two cells 1 and 2 back to back with a V-shaped mirror.