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Advances in Materials Technology: MONITOR

March 1993

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Distributed free to a targeted audience in developing countries

Dear Reader,

This is number 31 of UNIDO's state-of-the-art series in the field of materials entitled **SOLAR CELLS AND THEIR INDUSTRIAL APPLICATIONS**. This issue is an update to our previous *MONITOR* on SOLAR CELLS MATERIALS, which was published in 1987.

The main article for this *MONITOR* was written for us by Dr. M.R.L.N. Murthy from Semicon Tech Consultants in Bombay, India. Other articles were compiled and sectioned, as in the previous issues, under "Trends in Research and Recent Developments"; "Applications"; "Marketing"; "Publications" and "Past Events and Future Meetings".

Based on the earlier work of UNIDO in promoting solar energy technology, and specifically the recommendations of the Consultative Group on Solar Energy Research and Application (COSERA), the Government of Australia has made a proposal, including substantial financial contributions, to establish a centre for application of solar energy in Perth, Western Australia. This proposal was discussed in depth at a special COSERA Meeting, held in December 1992. The Meeting fully endorsed the concept of the Centre for Application of Solar Energy (CASE) and called for its urgent realization and strongly supported the proposal of Australia to establish the first CASE in Perth. It was also agreed that CASE should be planned as a network and initiatives should be undertaken to establish subsequent CASES. As far as possible, the Centre established in Perth will attempt to utilize and develop capabilities and facilities in developing countries. The Meeting called upon UNIDO and Australia to establish CASE in Perth as an international centre as early as possible and to carry out the necessary preparatory and pilot activities in support of the initiative. UNIDO and the Australian authorities have been in consultation on this matter with a view to carrying out the necessary actions to establish the Centre.

We want to emphasize at this point our appreciation to all our readers for their comments and suggestions. We always welcome your news on developments of new materials, announcements of new literature covering new materials and future meetings. We also welcome offers to write the main article for a future issue of our *MONITOR*.

Industrial Technology Development Division

CONTENTS

1. SOLAR CELLS AND THEIR INDUSTRIAL APPLICATIONS

by Dr. M.R.L.N. Murthy, Semicon Tech Consultants

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1. Introduction

Industrial and academic researchers have made rather impressive progress over the past 15 years in realizing advanced technologies in the field of photovoltaics, transforming the status of photovoltaic technology from exotic energy scenario to practical and usable energy on a commercial scale of operations.

Solar cell, the primary component of the photovoltaic equipment, converting sunlight directly into electricity, has been the focal point for research, and a variety of materials and a multiplicity of fabrication techniques were employed for achieving better conversion efficiencies.

Solar cell

A photovoltaic cell or solar cell is a semiconductor device which directly converts solar energy into electrical energy. The amount of solar energy reaching earth in 20 minutes equals the amount of energy consumed on the earth in one year. While the amount of irradiation in outer space is 1,353 w/m^2, on earth it is only 1,000 w/m^2 due to the absorption and scattering effect of the earth's atmosphere. Figure 1 shows the irradiation spectrum of wavelength on the earth's surface and airmass influence.

The principle of electricity generation in a photovoltaic cell is illustrated in figure 2. Part of the light beam (1) is reflected by the surface of photovoltaic cell. A short wavelength (2) after being absorbed by the surface creates an electron/hole pair. The electron and the hole recombine before they reach the P-N junction where they convert their energy into thermal energy (3) and (4) beams also create electron hole pairs. An electron/hole pair spreads out to the P-N junction where due to a strong electric field, the electron is carried to the N region and the hole to the P region. Then both regions generate photovoltaic energy which sends an electric current into the outside circuit through the electrodes located in each region.

A long wavelength beam (5) goes through the solar cell without causing an electric reaction. When it reaches the rear electrode it is absorbed and transformed into heat.

The amount of current (amperage) produced by photovoltaic cell is proportional to the amount of light falling on the cell. Thus current increases with the area of the cell as well as with the intensity of light. However the voltage depends on the material used. All silicon cells produce about 0.5 volts regardless of cell area.

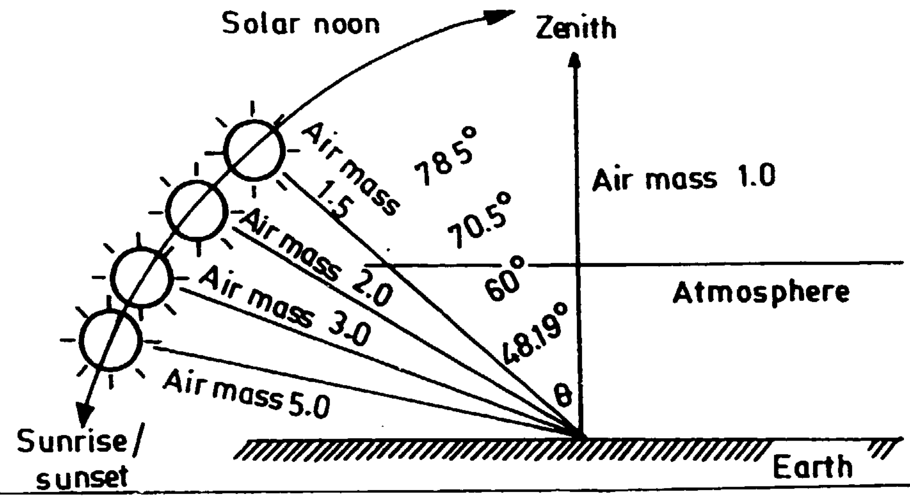
Although scientists have known of the photovoltaic principle for many years, the technology has always been prohibitively expensive - until recently. Major developments have been made in the last 15 years that have lowered the cost of photovoltaic cells and systems to the point that they are now economically preferable to the conventional power supplies in some areas. When first introduced in the 1950s, solar electricity cost was about US$ 2,000 per watt, reduced to about $60 per watt in 1976. That cost is now further reduced to $5 per watt and many experts are predicting costs as low as $1-$2 per watt by the turn of the century.

2. Photovoltaic module manufacturing technologies

Over the past 15 years several solar cell technologies have been developed all over the world and they can be broadly classified in the following categories:

1. Crystal silicon technologies

   (a) Single crystal silicon technology



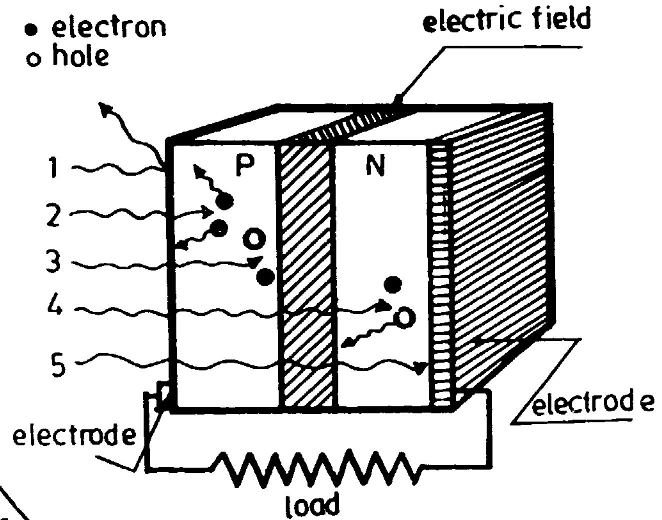


Fig. 2. Principle of Photovoltaic Cell

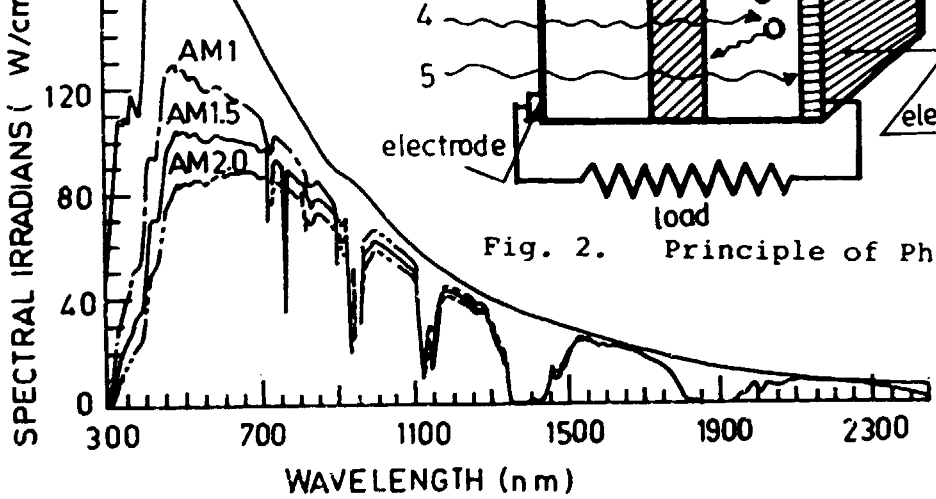


Fig. 1. Irradiation Spectrum

(b) Multi-crystalline silicon technology

(c) Sheet or ribbon technologies

2. Thin film technologies

(a) Amorphous silicon technology

(b) Semiconductor based thin film technologies (other than silicon)

Single crystal technology

With the advent of the Czochralski process of growing large silicon crystals (100 mm diameter and 1.0-1.5 m long crystal ingots) single crystal technology has been the mainstay for large-scale solar cell production by photovoltaic industries.

The fabrication of solar cell and module involves three stages: first the fabrication of single crystal silicon wafer; secondly, fabrication of single crystal silicon PV cell and finally fabrication of PV module.

Fabrication of single crystal silicon wafer

As shown in flow chart figure 3, the first step is preparation of metallurgical grade silicon by mixing silica (SiO_2) with carbon (coke or charcoal) and deoxidized in arc furnace. The resulting silicon (97-98 per cent purity) is processed by the trichloro silane method to produce high purity poly silicon Czochralski method (CZ) or float zone (FZ) method is employed to grow single crystals. The major percentage of crystal silicon for PV use is produced by CZ process. Silicon crystal production is a well-established industry in many countries.

The specifications of the crystal ingots required for photovoltaics are less stringent than that of crystals required by the semiconductor industry producing integrated circuits. The heads and tails of the semiconductor grade silicon crystal are used for producing solar grade crystal ingots.

The crystal ingots are sliced by either ID saw to slice wafers in the range of 300 to 450 microns or wire saw to get thin wafers in the range of 120-200 microns.

Fabrication of solar cell

Solar cell is the most important element of the photovoltaic device and the crucial part is diffusion to create the P-N junction. After the initial etching and texturing process steps on the silicon wafer, a thin layer of phosphorous doped silicon is brought into contact with a layer of boron doped silicon in the diffusion process to create the P-N junction. Minute quantities of boron and phosphorous (one part in a million) are used as dopants. Electrode printing is done using Ag pastes and fixed for the electrode formation and solder coated. After the cell is given its metallic contacts, the front surface is provided with an anti-reflective coating. Since Si is highly reflective, throwing back 35 per cent of light that strikes it, the cells are coated with a thin layer of silicon monoxide or titanium dioxide to counter the reflection.

Photovoltaic module

The silicon PV cells are packaged into modules. Packaging is done to protect the PV cell from radiation, temperature, humidity, salt and dust. After the soldering and interconnecting the electrodes, the cells are sandwiched between a tempered glass (low iron, highly transparent) and sheet of EVA (ethylene vinyl acetate) for mechanical bonding and encapsulation. These are followed by cushioning sheets of glass fibres, another layer of EVA and one of Mylar which provides the dielectric insulation important in high voltage systems. Finally the module's backing is applied in the form of a Tedler/aluminium foil/polyester laminate to seal the unit against moisture. The module is placed in a lamination chamber which performs the functions of evacuating all air from the module and then heat-sealing the layers into an integral unit. Various process steps of fabricating crystals, wafers, solar cells and modules are shown in figure 3.

Multi-crystalline technology

Fabrication of multi-crystalline solar cell is generally on the same lines as that of crystal silicon technology, but for some modifications introduced to counter the problems faced by grain boundaries, stresses, impurities, etc., in the cast silicon process technologies, which are reviewed elsewhere in this report.

Multi-crystalline silicon

Multi-crystalline material at industrial level is being produced specially for photovoltaic applications for the last 10 years but in limited quantities. While Wacker Chemi and Solarex Companies are some of the companies which started producing multi-crystalline material by the casting process, over the last five years; other companies, such as Crystal Systems, IBM, Photowatt, OTC, Polyx, Crystalox, have come up with silicon cast ingots employing various techniques, namely, heat exchanger method, directional solidification cold crucible induction casting, etc. Several ingots produced are in the range of 80-120 kg materials, generally with square cross sections of 44x44 cm or 55x55 cm and throughputs getting better and better. Crystalox company has announced recently their plans to produce 230 kg ingots soon.

Slicing

Both crystalline and multi-crystalline ingots are sliced employing ID saw. However, during the last five years wire saws have been developed which reduces the

Kerf loss to a great extent, to as much as 120 microns compared to the best values of 300 microns when sliced by ID saw. Another innovation in slicing technology is Fixed Abrasive Slicing Technique (FAST) which was recently developed by Crystal Systems. FAST utilizes a multi-wire blade pack with each wire held in a frame with equal spacing and tension, and slicing is achieved by reciprocating the blade pack in a slicer head. The major process techniques developed as well as the slicing methods employed along with results on capacities of ingot growth slicing time and thickness have been detailed in table 1.

Ribbon and sheet technologies

Ribbon silicon crystal growth was envisaged mainly to reduce the wastage of precious silicon crystal which occurs during the slicing process (of the order of 30-40 per cent). A variety of techniques were developed to grow ribbons or sheets of crystal silicon.

Mobil Solar Energy Corporation employ graphite or ceramic die (shaping guide material) having a thin slit through the centre lowered into molten silicon. The silicon is drawn up through capillary action. A seed crystal touching the melt at the top is slowly withdrawn upwards resulting in ribbon crystal growth; the schematic diagram of this process is shown in figure 4. Mobil solar produces nanogon wafers where they get nine ribbon crystals in one run.

Westinghouse Corporation uses the dendritic web method. Unlike the die used in the EFG process this method employs two dendrites - elongated starter crystals - are lowered into the silicon. As they are drawn up a sheet of crystal silicon is formed between them. A schematic diagram of the dendrite web process is shown in figure 4.

Hoxan Corporation from Japan has come out with a novel process called spin cast method to make 10x10 cm silicon wafers. A specified amount of molten silicon is allowed to fall from a quartz funnel onto a graphite mould with a 10x10 cm cross-sectional cavity. The mould is spun as the silicon melt is dropped to form a 10x10 cm silicon wafer. The silicon solar cell fabricated using the spin cast wafers have shown conversion efficiencies in excess of 10 per cent. A schematic diagram of the spin cast silicon crystal growth is shown in figure 4.

Amorphous silicon cell

Amorphous silicon has a high optical absorption coefficient, which means most of the sunlight falling on it is absorbed after passing through a very short distance - less than a micrometre in hydrogenated amorphous silicon compared to 50 times that distance in crystalline silicon for the same amount of light to be absorbed. Another advantage is the ease with which it could be deposited over large areas as well as on curved substrate surfaces and the material and energy requirements are low.

Amorphous silicon solar cell fabrication steps

The basic structure of the A-Si solar cell consists of thin layers of P-I-N materials sandwiched between a transparent top contact and metallized bottom contact deposited onto a glass superstrate. The basic fabrication steps are:

(1) Deposition of TCO layer on glass using APCVD process;

(2) Patterning of oxide layer by laser scribe;

(3) Deposition of P-I-N layer by PECVD process;

(4) Patterning of P-I-N layer by laser scribe;

(5) Metallization by vacuum evaporation or screen printing;

(6) Patterning of metallized layer by laser scribe or screen printing; and

(7) Encapsulation as shown schematically in figure 5.

Semiconductor based thin film technologies other than silicon

CIS, Cds, CdTe are some of the compounds that are promising materials for conversion of sunlight into electricity in view of their high absorption coefficient for sunlight, relatively stable cells without the problem of degradation like A-Si cells and also because of the simpler technologies required.

A typical thin film solar cell is made of Glass/Mo/CIS/CdS/ZnO with the CIS layer of few microns thickness and a thin CdS layer of about 500Å to act as window. The Mo layer acts as the back contact material for CIS and ZnO layers on CdS serves as the top contact.

Fabrication steps for CIS solar cell:

(1) Vacuum evaporation of Mo (0.5-2.0μ) on glass;

(2) Patterning by chemical etch or laser scribe or photolithography;

(3) Deposition of CIS (P-type) to a thickness of 2 microns on the patterned Mo back contact by depositing Cu (0.2μ) and In (0.45μ) as stacked layers using evaporation process;

Table 1

Multi-crystalline ingot growth techniques

Group	Technique	Features	Wafering	Year
Wacker	WICP (S!LSO)	Two different containers Melting and crystallization Directional solidification VGR:0.5, IW:120, IS:43x43x28	MBS CR: 3.6 Y: 0.8 WT: 250 300	1975 [1] 1988 [2]
Solarex	UCP (SEMIX)	High purity low-cost crucible automated process control Directional solidification VGR:2.1, IW:30 IS:23x23x18	Wire saw W/C: 20 W/T: 250	1976 [3] 1988 [4] 1988 [5]
Crystal Systems	HEM	High purity, slip-cast silica crucible Directional solidification VGR:0.8, IW:40, IS:32x32x17	FAST W/C: 32 W/T: 100 Y: 1.08	1978 [6] 1983 [7]
IBM	DS	Bridgman-Stock-barger method carbon crucible CMB/vitreous GS:5.5/0.7, IW:0.58/0.139, IS:5x5x13/5x5		1979 [8]
Lab. de Marcoussis CGE Photo-watt	CAST (POLYX)	Directional crystallization Liquid encapsulation crucible IW:58, IS:44x44x13	Wire saw WT: 140 170	1980 [9] 1987 [10]
NEC/OTC	MRC	Directional crystallization Si_3N_4 powder mold releasing agent IW:60, IS:33x33x22	MWSS CR: 1.5 KL: 230	1981 [11] 1987 [12]
Crystalox		Coated quartz crucible 44x44x20cm^3, 90kg		1991 [13]

Abbreviations

WICP:	Wacker ingot casting process;
MBS:	Multiblade slurry sawing;
UCP:	Ubiquitous crystallization process;
HEM:	Heat exchanger method;
FAST:	Fixed abrasive slicing technique;
MRC:	Mold releasing casting technology;
MWSS:	Multi-wire slurry sawings;
GS:	Growth speed (mm/min);
VGR:	Volume growth rate (kg/h);
IS:	Ingot size (cm);
IW:	Ingot rate (kg);
WT:	Wafer thickness (m);
W/C:	Wafers (cm 1);
CR:	Cutting rate (M2/h;
Y:	Yield (m^2/kg);
KL:	Kerf loss (m)

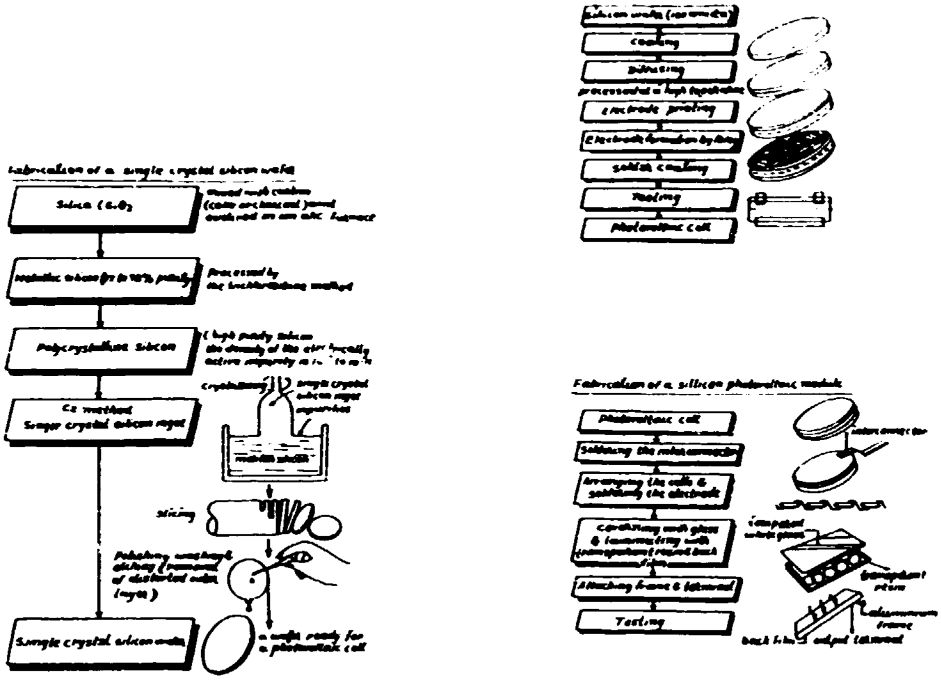


Fig. 3. Various process steps of making crystals, wafers, cell fabrication and module making

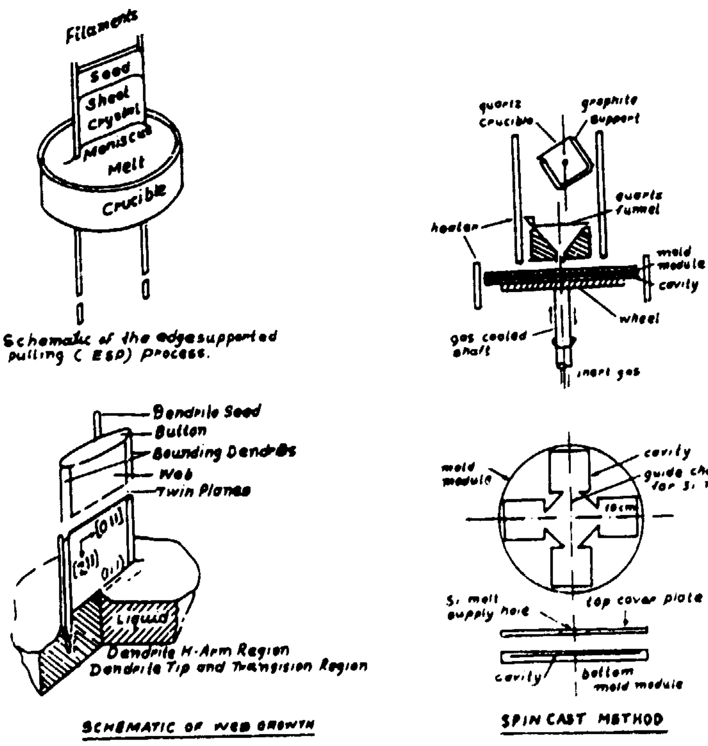
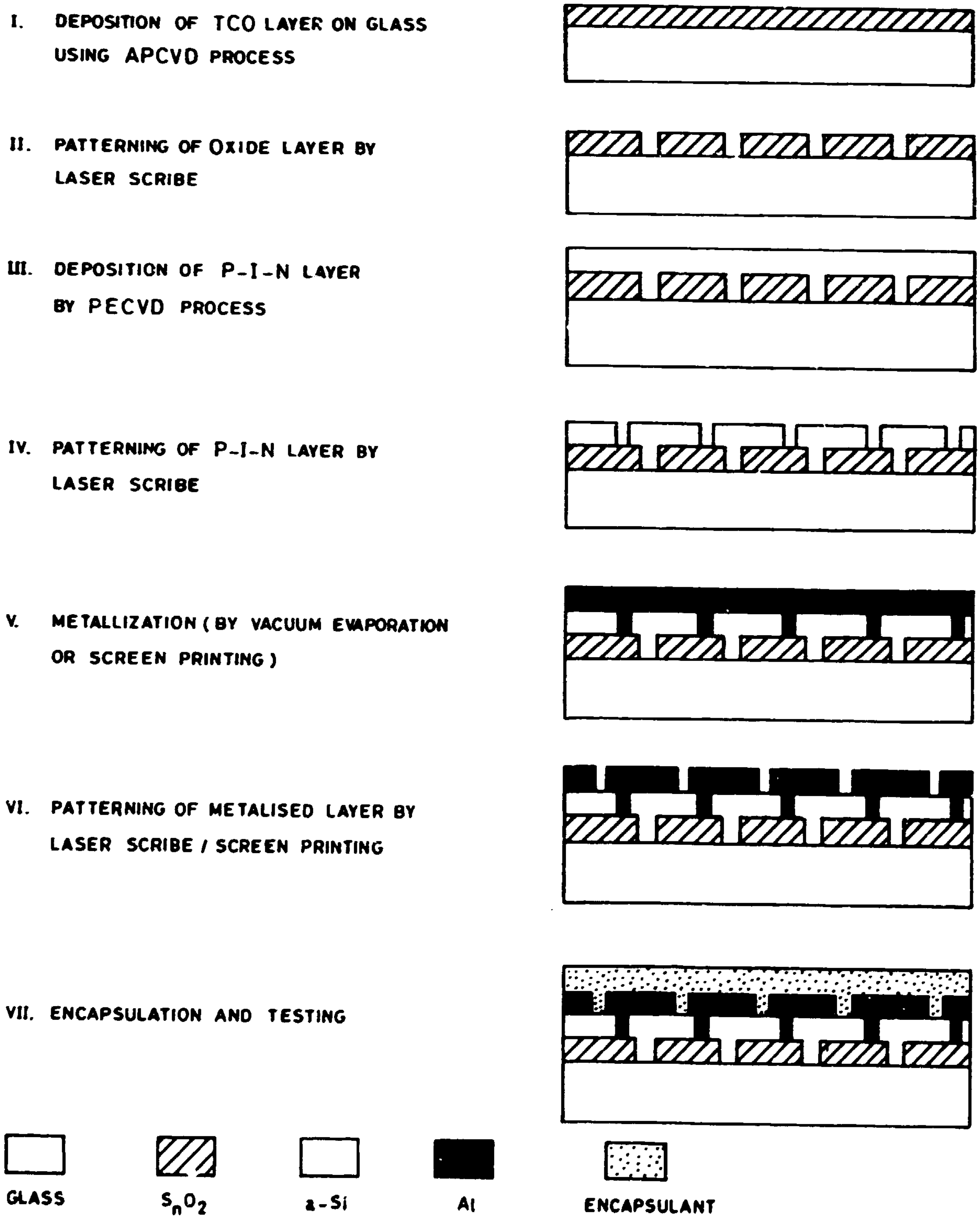
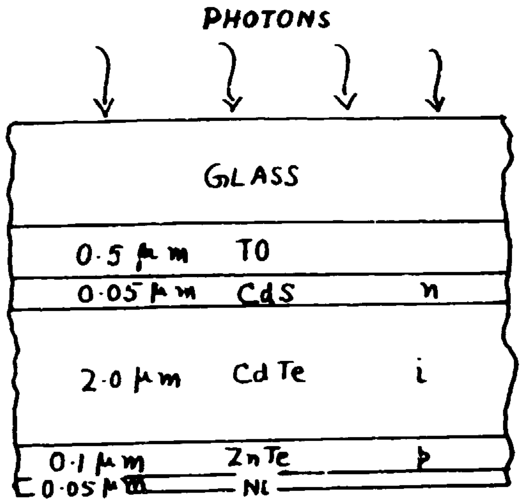


Fig. 4. Schematic diagrams showing various Si ribbon growth techniques

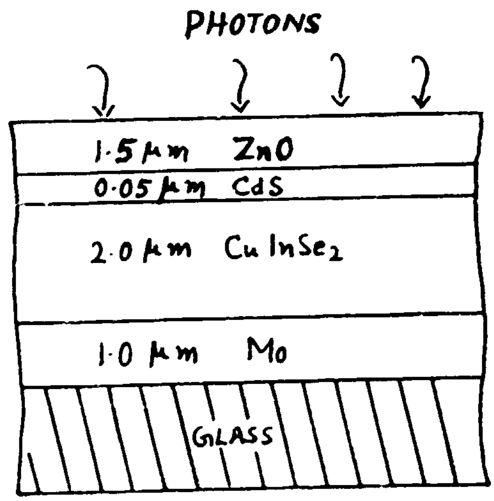


PROCEEESS STEPS IN A-Si MODULE FABRICATION

Fig. 5. A-Si Solar Cell fabrication steps



CdTe cell structure



CIS

Fig. 6. Schematic of CdTe and CIS cells

(4) Selenised under H_2Se atmosphere around 400° C forming $Cu\ In\ Se_2$;

(5) Deposition CdS through vacuum deposition;

(6) Deposition of ZnO over CdS by R.F. sputtering or MOCVD; and

(7) Encapsulation with EVA.

Concentrator techniques

By increasing the amount of sunlight impinging on the solar cell one can decrease the more expensive semiconductor material used in solar cell. Optical concentration systems of lenses and mirrors to focus sunlight on high efficiency solar cells. Shown in figure 7 are three arrangements:

(a) A parabolic trough reflector focusing sunlight on a string of cells and the reflector is rotated to follow the sun;

(b) Linear fresnel lens focusing sunlight on the row of cells and the whole device turns to track the sun; and

(c) Point focusing by fresnel lens to concentrate sunlight on single cell and using a two-axis tracking to follow the sun.

Other arrangements include multiple junction tandem cell wherein three or four cells of different materials are stacked one above the other; the top cell is activated by higher energy photons, the next cell down converting photons of lesser energy and the bottom-most cell activated by the further lower energy photons. This cell can achieve very high efficiencies and is economically viable with the use of thin films. Experts view that photovoltaic concentrator collectors could be the first photovoltaic technology to be cost effective for utility scale powerplant applications.

The concentrator cell represents approximately one-third of the cost of a typical concentrator collector and the cell efficiency is the dominant factor concerning collector performance (14). A review of concentrator cell technology is presented by King (15). Table 2 summarizes the concentrator cell efficiencies measured at Sandia National Laboratories presented by Gee, the highest efficiency achieved by Boeing (16) around 34 per cent using GaAs/GaSb material cell.

3. Solar cell technologies

Review of the state of the art of cell technologies

Solar cells are made using a number of materials dominated by silicon and they are designed dictated by the parameters for achieving high efficiency. The junction or barrier is the most critical component of solar cell and the cells characterized by the material used for junction. There are four basic junctions with several variations.

Homojunction: In silicon solar cell the junction is made of very thin region at the boundary between the p-doped and the n-doped portions of silicon. Such a junction within a single material is called homojunction.

Heterojunction: If dissimilar materials such as a layer of copper sulphide is deposited on a cadmium sulphide the contact zone is called heterojunction.

Schottky barrier: Junction established between a semiconductor material and metal is called Schottky barrier.

MIS junction (metal insulator semiconductor): A thin layer of insulator such as titanium oxide is sandwiched between a metal and a semiconductor to form MIS junction.

A variety of materials, Si, GaAs, semiconductor compounds CIS, as well as amorphous silicon and other thin films, have been used for fabricating solar cells at the industrial level.

Crystal silicon solar cell

Till now the best conversion efficiencies are reported for solar cells based on crystal silicon. Standard cell fabrication technique has been described in the earlier chapter. Here the criteria for developing high efficiency cells and the various techniques employed to achieve higher efficiencies would be described.

Criteria for high efficiency cells: Low resistivity, high lifetime silicon material is an ideal candidate. Reducing surface recombination velocity, band gap narrowing, effect of cell thickness, impurities are some of the factors having a direct effect on conversion efficiencies. Also are the energy loss mechanisms in solar cells such as photon losses, carrier losses and power losses contributing to degradation of cell efficiency. Some of the techniques developed to overcome these deficiencies are described here.

- Surface recombination is reduced by passivation using thermally grown SiO_2 by Blakers (17).

- Stanford University group (18) has boosted the performance of its point contact cell structure shown in figure 8 by incorporating texturing on the illuminated cell surface. This improves light trapping within the cell greatly increasing the current density in these cells.

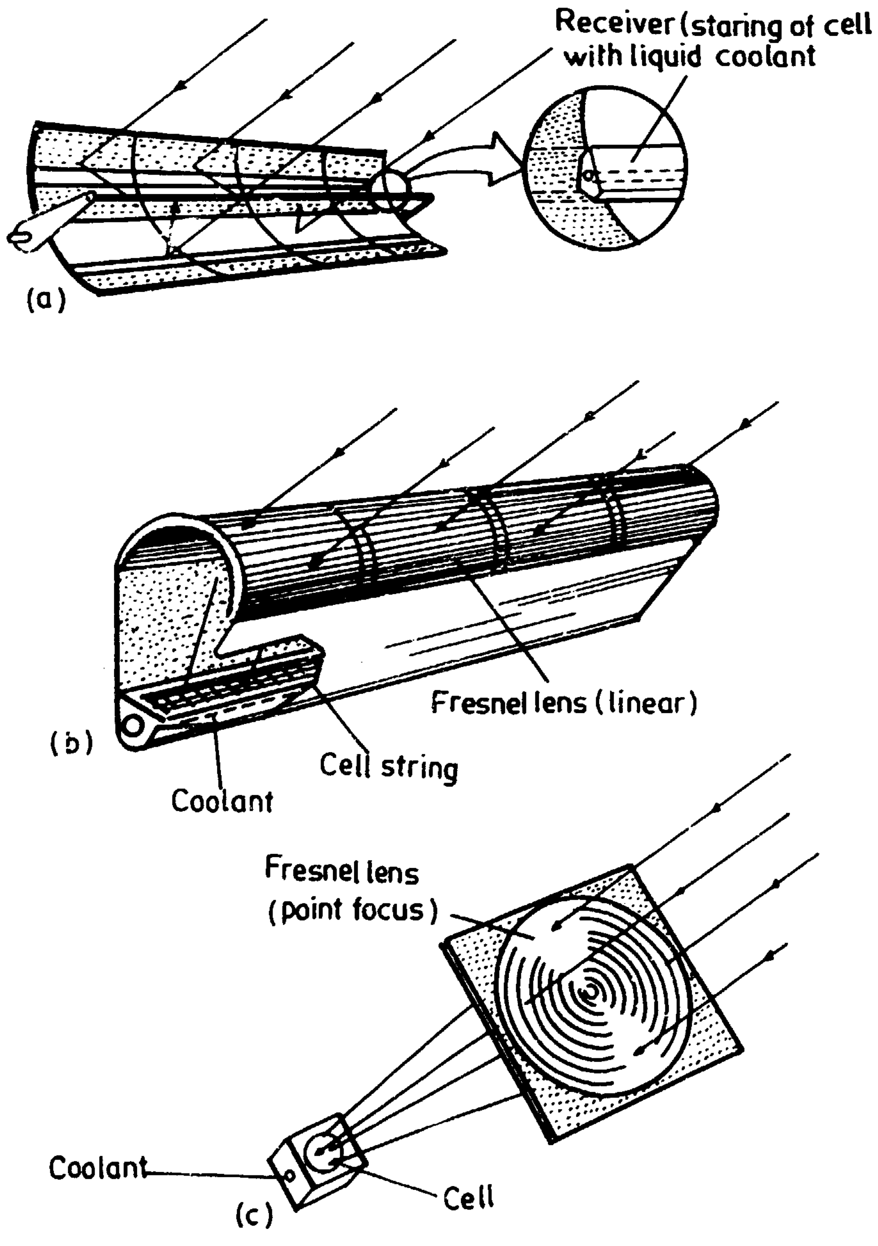


Fig. 7. Optical concentration systems focussing light on solar cells.

Table 2

Status of concentrator cells' efficiencies. High-p and low-p refer to high and low resistivity; FZ, PX, and Cz refer to float-zone, polycrystalline, and Czochralski; PCG refers to prismatic coverglass; and MSMJ refers to mechanically stacked, multijunction cell.

Developer	Material	Cell type	Area cm^2	Conc. suns	Eff. %
		Low-concentration cells			
UNSW	FZ, Si	Laser grooved, PCG	20.0	20	22.6
Solarex	CZ, Si	Low-p, PCG	38.4	20	20.2
Solarex	PX, Si	Low-p, PCG	39.5	20	17.5
Astropower	Cz, Si	Low-p, PCG	39.6	20	17.8
		Mid-concentration cells			
Stanford	FZ, Si	High-p, back contact	0.15	140	28.2
UNSW	FZ, Si	Low-p, PCG	1.58	125	25.2
SERA	FZ, Si	High-p, back contact	0.065	65	23.9
Solarex	FZ, Si	Low-p, PCG	1.58	150	21.5
		High-concentration cells			
Varian	GaAs		0.126	403	28.1
Varian	GaAs	PCG	0.126	206	29.2
Spire	GaAs		0.317	200	28.7
Sandia	GaAs/Si	MSMJ, Varian, Stanford	0.317	500	31.0
Boeing	GaAs/GaSb	MSMJ	0.053	100	34.2

- The University of New South Wales (UNSW) cells use micro-grooved passivated emitter solar cell (μgPESC) (19) and use of metallization fingers gives an optical advantage as the angles are such that light striking some areas of the finger metallization is reflected onto the active cell area reducing shading losses.

- Laser grooved buried contact solar cell shown in figure 9 developed by Martin Green (20), UNSW, are textured, lightly diffused and oxidized. Grooves are then cut into the top surface of the wafer through the oxide and diffused layer using laser scriber. The grooved areas are cleaned by etching followed by a second diffusion heavier than the first one. Cell processing is completed by plating electroless Ni and Cu to the grooved areas and near the cell using the oxide as plating mask. The same sequence is followed with the oxide replaced by nitride which yielded better anti-reflection properties. Alloyed aluminium rear contracting scheme is used in this structure. Efficiencies reaching 20 per cent have been reported with this approach.

Double-sided laser grooved cell

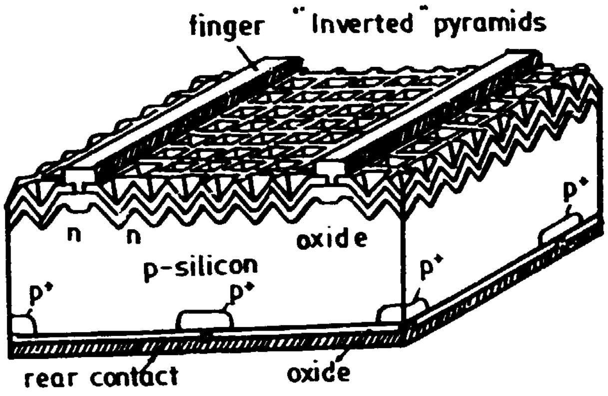
In this cell the alloyed aluminium rear contact scheme is replaced by an oxide passivated structure, similar to that used in PERL cell. Good progress has been made in developing the "double-sided" laser groove cell shown in figure 10, a potentially low cost to ultra-high efficiency cell.

The world record of conversion efficiency at present has been achieved by Passivated Emitter Rear Locally diffused cell (PERL) and developed by Green's group (21), which is 24.2 per cent. The structure of PERL cell is shown in figure 11.

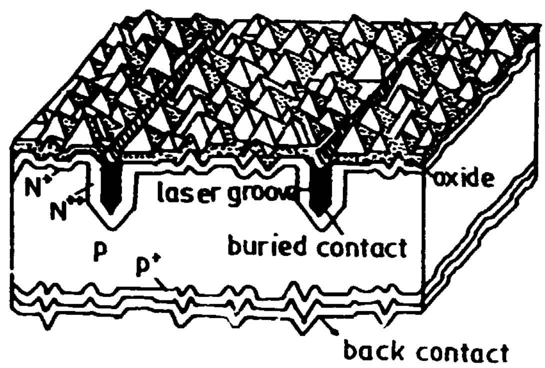
Progress in high efficiency single crystalline solar cells are presented in table 2 (a).

Spherical solar (TM) cell process

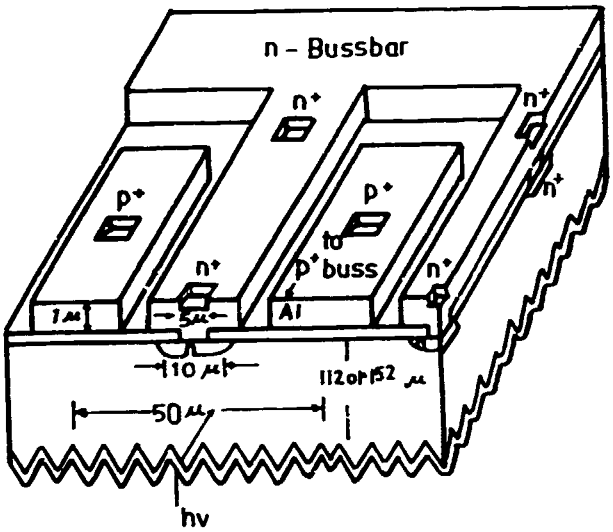
Texas Instruments reported very recently spherical solar (TM) (22) cell process. Figure 12 shows the silicon purification and sphere formation process. Shown in (A) is feed stock with impurities black dots in grains. In (B) the particles become rounded on melting. Upon



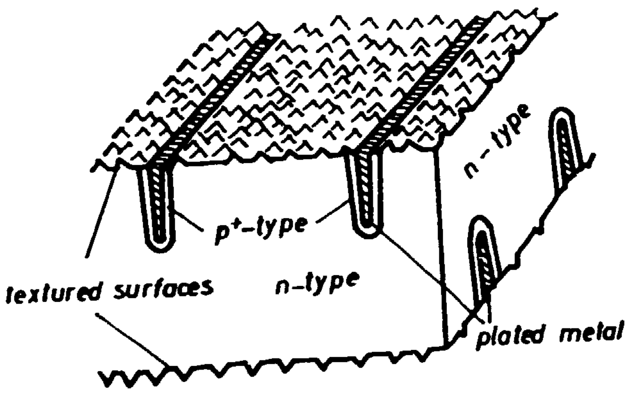
PERL CELL



LASER GROOVED, BURIED CONTACT
POLAR CELL



STRUCTURE OF THE POINT CONTACT CELL



"DOUBLE SIDED" LASER GROOVED

Fig. 8. Structure of the point contact cell

Fig. 9. Laser grooved burried contact cell

Fig. 10. "Double-sided" laser grooved cell

Fig. 11. Structure of PERL Cell.

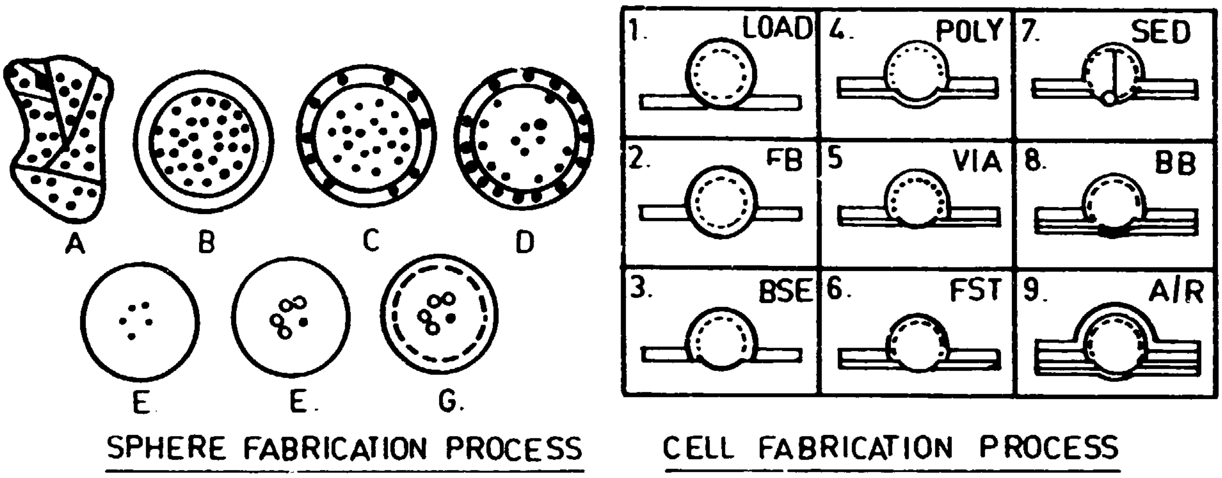


Fig.12. Spherical solar (TM) cell process

Table 2 (a)

Progress in high efficiency solar cells

Voc (mV)	Jsc_2 (mA/cm^2)	FF	(%)	Notes	Year, Ref.
641	35.5	.822	18.7	MINP	1983, [2]
652	36.0	.811	19.1	PESC	1983, [3]
661	38.3	.824	20.9	g-PESC	1985, [4]
681	41.5	.786	22.2 (27.5)*	BPC	1986. [5,6]
647	39.2	.808	20.5	V-grooved	1987, [7]
703	40.3	.814	22.8	PERC	1989, [8]
696	42.9	.810	24.2	PERL	1990, [9]

AM 1.5, 1 sun, [( )* Under 100 suns concentrations]

solidification single crystal spheres are formed (C&D). The many impurities found on the surface are ground away by mechanical means (E). The melt/removal sequence is repeated until the desired purity is achieved. Solid state treatments such as denuding, oxygen precipitation and phosphorous gettering are used to fix the remaining impurities inside the core of sphere (F). Finally a deep N^+ layer is formed with phosphorous diffusion. The spheres are about 0.75 mm in diameter.

Cell processing steps

Embossing a 0.06 mm thick Al foil embossed with a hexagonal pattern and etched with potassium hydroxide so that apertures appear as shown in figure 12 (1). The spheres are thermomechanically bonded into the foil in the front bond process (2). A back side etch exposes the p-type core of each sphere using a chemical etch for Si and the Al foil as a self-regulating etch mask (3). A thin layer of polymide is applied to the back of the cell and cured to a solid film (4).

Selective abrasion on the tip of the sphere is used to etch away the heavily doped region from the deep N^+ diffusion. A selective electro dissolution process (SED) is used to isolate the small fraction of shunted spheres in the MG feed stock. The back bond (BB) is applied by bonding a second Al foil to the rear of the cell and finally an AR coating of titanium dioxide. This cell has been reported to achieve 11.3 per cent efficiency and is expected to go higher with stabilization of the cell formation process.

Multi-crystalline solar cells

A typical processing sequence for multi-crystalline solar cells starts with etching the multi-crystalline substrates to get rid of sawing damage followed by gettering with heavy phosphorous diffusion and junction is formed. Then a back surface field is formed and the back electrode is deposited by screen printing and alloying of aluminium. The front electrode is formed by silver screen printing followed by anti-reflection coating usually titanium dioxide deposited by CVD. Finally a hydrogen passivation treatment is included in the process sequence.

- Gettering: phosphorous pre-treatment is expected to increase the diffusion length exceeding 150 m in multi-crystalline substrat (23) specially at an optimum temperature of 900°.

- Junction formation: advanced silicon cells make use of optimized emitter, wenham (24) have suggested the use of a screen printed metal grid as mask in dry etching step in which emitter in the active regions is etched back. Also used is the method to obtain selective emitter based on the selective oxidation of silicon using Si_3N_4 mask.

- Back-surface-field and back electrode: as future cells tend to be thinner and have longer diffusion lengths the surface recombination of the rear surface must be reduced which is done by a pp^+ back surface field which could be effected by boron diffusion.

The second way is the use of gridded back electrode with passivated non-contacted areas to reduce the surface recombination velocity. The PERC and PERL cells proposed by UNSW (19) have demonstrated that an oxidized p-type back surface with selective contact openings yields higher open circuit voltages.

- Hydrogen passivation: hydrogen atoms introduced into Si substrate act as terminator to the dangling bonds associated with the crystal defects. Ion implantation (25), plasma hydrogenation in hydrogen glow discharge and hydrogenization (26) using a plasma deposited silicon nitride layer are some of the methods employed for hydrogen passivation.

- Sharp achieved 16.4 per cent efficiency by incorporating surface grooming as well as double layer anti-reflection coating (27).

- Hitachi obtained n=16.8 per cent with a hybrid contact cast cell having an anode and a cathode electrode on the back surface as well as a cathode electrode on the front surface.

- Bifacial silicon nitride solar cell (28) has SiNx film deposited on the back and front surfaces of the cell and these indicate efficiencies 10 per cent on 20x20 cm area substrates. Schematic diagrams of these cell structures and efficiencies are shown in figure 13.

Progress in multi-crystalline solar cells developed in several laboratories and industries have been presented in table 3.

Amorphous silicon A-Si solar cell

Development of A-Si was first reported by Wronski (37) in 1976 and cell efficiency of 2.4 per cent was reported for single junction with p-i-n device and a commercial product has come out in 1980 - pocket calculator by Sanyo, Japan.

The single junction A-Si cell with typical values of thickness of various layers p-i-n are shown in figure 14. Progress made in single junction device has been achieved through a sequence of improvements in material quality and innovative device structures pushing the conversion efficiency from 2.4 per cent in 1976 to about 13 per cent in 1991.

Short-circuit current, open circuit voltage and third parameter fill factor play a major role in optimizing the device efficiency.

Short-circuit current (J_{sc}) is controlled mainly by optical enhancement and quality of the intrinsic layer. The quality of i-layer has been shown to improve by controlling the incorporation of impurities during deposition. The quality of the layer controls the spread of space charge where field-assisted collection occurs.

Open-circuit voltage

Voc is determined primarily by the built-in potential and by recombination of photo-generated carriers.

The built-in potential (V_{bi}) is strongly controlled by the p-i and i-n interfaces. Higher band gap p- layers using L-SiC:H, super lattice p-layers, and highly conducting micro crystalline p-layers are employed to improve V_{bi}. Lower blue response has been attributed to carrier recombination near the p-i surface. Blue response has been improved by incorporating a thin graded layer of L- SiC-H between the p- and i- layers.

Fill factor (FF)

Minimizing the series resistance and maximizing the shunt resistance optimizes the fill factor.

Multijunction and hybrid combination solar cells

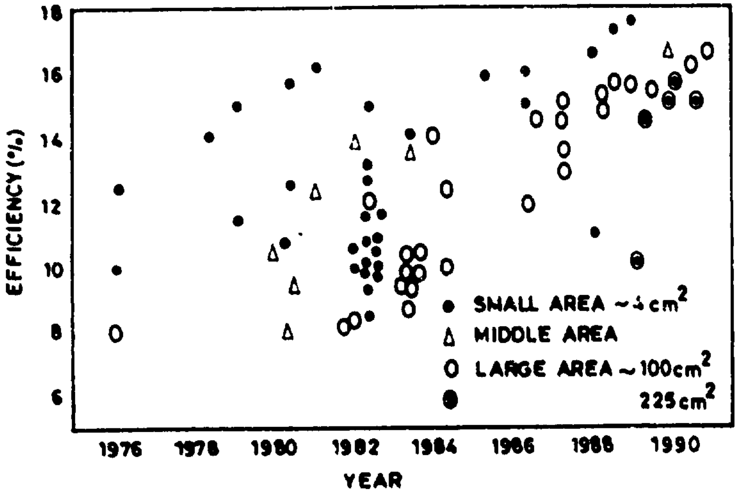
Multijunction and hybrid combination devices exhibited higher conversion efficiencies resulting from enhanced spectral response and a steeper potential gradient within the device.

Also a variety of fabrication methods and materials were introduced. Separated reaction chamber was developed by SANYO to prevent mutual inter-mixing of impurities such as B and P (38). A separated ultra-high vacuum (UHV) reaction chamber system has been developed to reduce the impurity concentration (39) called super chamber which reduced impurities from about 10^{19-20} to about $10^{18} cm^{-3}$ thus improving film quality. Other fabrication methods include:

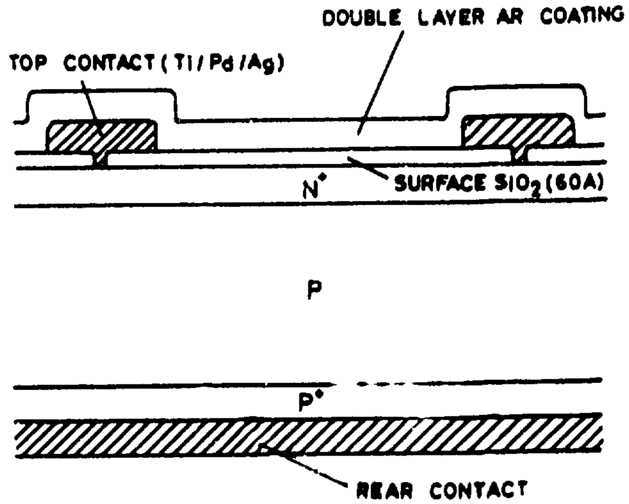
- Photo - CVD method (40)
- Radical - CVD method (41)
- Electron cyclotron resonance method (42)

To utilize sunlight effectively both narrow and wide band gap materials such as L - SiG and L - Sic. The quality of these materials have been improved by H_2 dilution method (43).

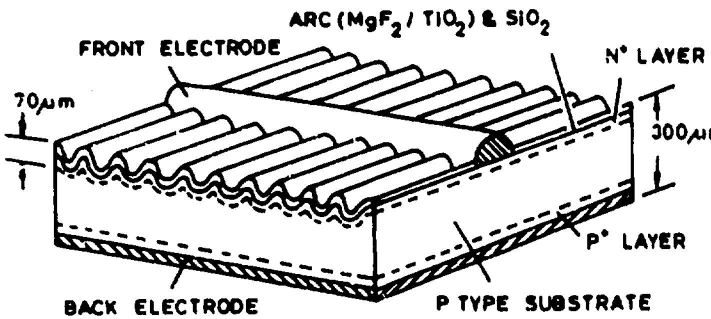
In order to increase spectral response in the short wave length region a cell structure using a wide gap p-type SiC, figure 15 (a), was developed by Osaka University (44). A super lattice structure p-layer, figure 15 (b) (45), and micro-crystalline SiC p-layer, figure 15 (c) (46,47), have been employed. To increase spectral response in long wave length region a textured



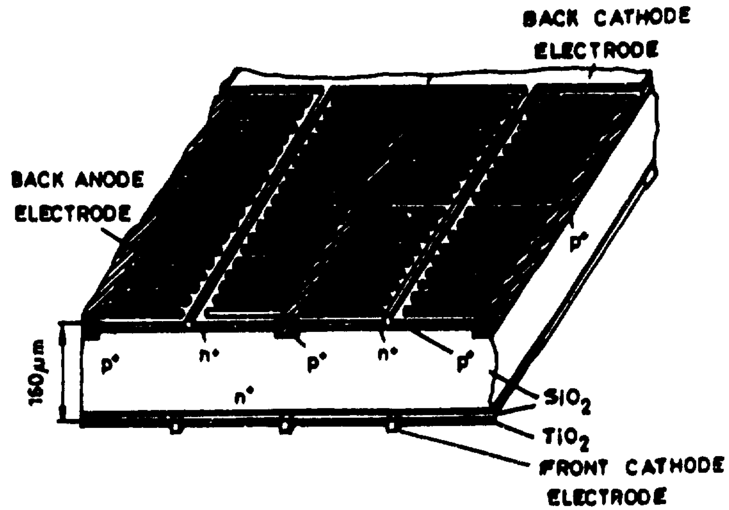
PROGRESS OF MULTICRYSTALLINE SILICON SOLAR CELL PERFORMANCE



STRUCTURE OF UNSW'S SOLAR CELL

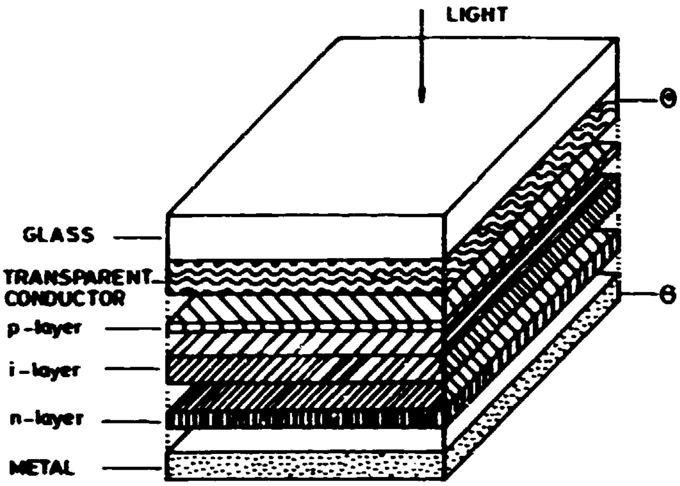


STRUCTURE OF SHARP'S SOLAR CELL



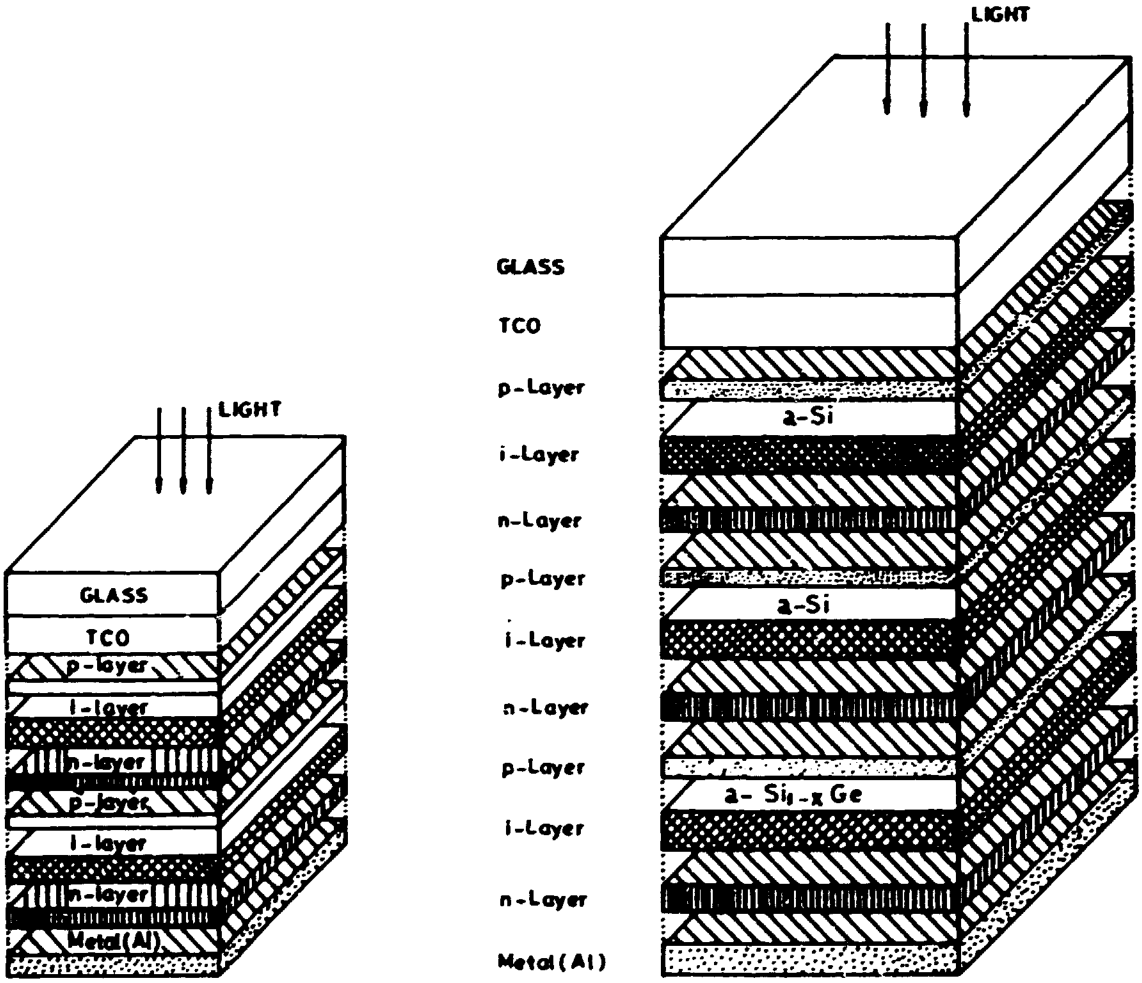
STRUCTURE OF HITACHI'S SOLAR CELL

Fig.13. Schematic diagrams of multicrystalline cell structures and efficiencies



Glass Superstrate	≈ 3 mm
TCO(SnO_2/ZnO)	≈ 5000 Å
p-a-Si_xC_{1-x}:H	≈ 150 Å
i-a-Si :H	≈ 3500 Å
n-a-Si :H	≈ 200 Å
Chemical Diffusion Barrier	≈ 100 Å
Al Bottom Contact	≈ 3000 Å

TYPICAL STRUCTURE OF A-Si SOLAR CELLS



(A) (B)

STRUCTURES OF A) 'SAME BANDGAP'
B) 'DIFFERENT BANDGAP' MULTIJUNCTION DEVICES

Fig.14. Schematic of cell junctions with single and difference band gaps.

Table 3

Progress of multi-crystalline silicon solar cell

G: Global

Group	Substrate	Year	Cell Fabrication Process	Area (cm^2)	Eff. (%)	AM	Ref.
AEG	SILSO	1989	Buried contact Laser grooved, SiNx, Ni/Cu	11.4	13.6		[29]
Solarex	SEMIX	1984	TiPdAg, Ta_2O_5/MgF_2	10x10	14.1		[30]
Crystal Systems/ MSEC	HEM	1983	P diff., plating, SiNx	44.65	13.49		[7]
Lab. Marcoussis CGE/Photowatt	POLYX	1986	Standard process	1x2 10x10	>15 >12		[31]
Crystalox	Crystalox	1991	Standard process	10x10	13.2		[13]
Univ. NSW	SILSO	1988	P pretreatment, P diff., oxide passivation TiPd+Ag plating, MgF_2/ZnS	4.1	16.6	1.5G	[32]
	OTC	1989		2x2	17.8		[33]
Sharp	OTC	1991	Grooved, oxide passiv. Elec.4%, MgF_2/TiO_2	10x10	16.4	1.5G	[27]
Hitachi		1991	Hybrid contact cell Front & back cathode elec.	10x10	16.8	1.5G	[34]
Kyocera	OTC	1990	BSNSC, uneven surf. Elect.; evap. 5%, MgF_2/SiN_x	15x15	15.6	1.5G	[35]
		1991	BSNSC, uneven surf. Elec.; print 5%, MgF_2/SiNx	15x15	15.3	1.5G	[36]

TCO was used, figure 15 (d), and a multi- gap structure was used, figure 15 (e) (48).

A combination of A-Si and other material such as poly Si or Cu In Se_2 was developed, shown in figure 15 (f) and (g) (49,50), which resulted in enhanced open circuit voltage.

Another development using A-Si cell is a see-through A-Si module (51) which has microscopic holes spaced uniformly on an integrated type A-Si module. This generates electric power while allowing light to pass through. The through hole contact (THC) integrated type A-Si solar cell module with the technology of see-through A-Si sub-module, the schematic diagram is shown in figure 16.

Light-induced degradation

It was reported that reducing impurities such as O_2 and N_2 (52) and also reducing Si-H_2 bond density significantly decreased degradation (53). Tandem structure using blocking layers was also proposed (54) to prevent degradation.

The present status of various cell technologies is shown in table 4, including the parameters such as Voc, Jsc, FF, area, efficiency and description of cell structures including hybrid, tandem configurations. Figure 17 shows A-Si efficiencies for various types of junction structures (38). A steep rise is seen with the introduction of A-Si alloy structures.

Semiconductor thin film cells Cu In Se_2 and CdTe

Schematic diagram showing typical values of thickness of films and deposition techniques to fabricate CIS and CdTe structures is given in figure 6.

The film CdTe cell: as many as 15 groups all over the world have reported cell efficiencies in the range 10-14 per cent various deposition methods such as atomic layer epitaxy, close spaced sublimation, electro-deposition, laser ablation metal organic CVD, physical vapour deposition, screen printing and spraying have resulted in high efficiency devices. A thin layer of dip-coated or solution grown Cd S has improved the blue response of Cd Te Cell from 500 nm to about 300 nm.

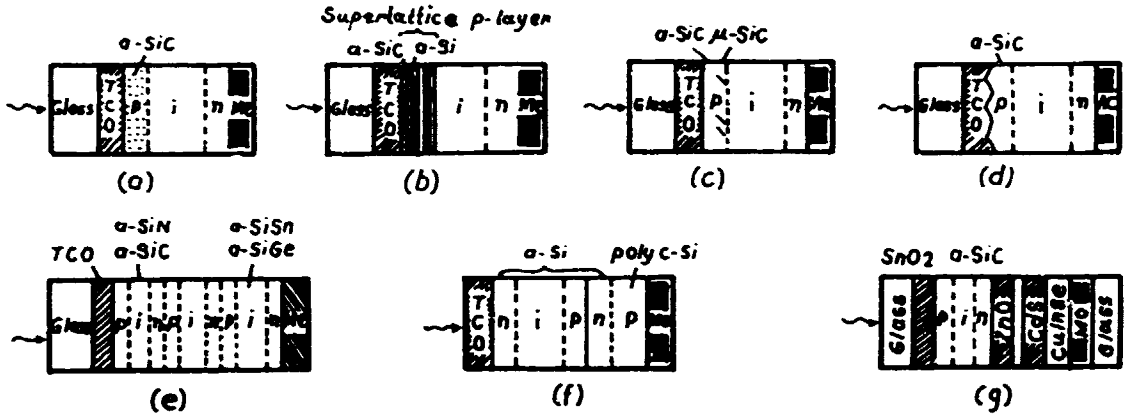
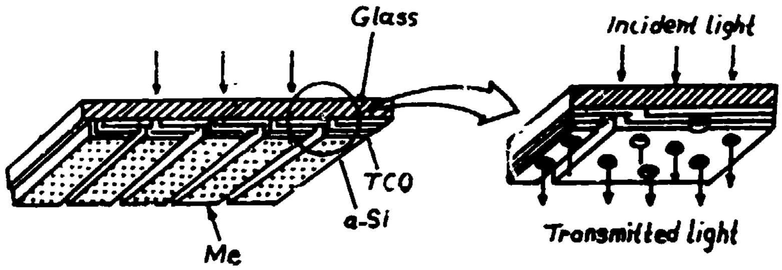


Fig.15. Structure of A-Si cells devised for high spectral response in longwave length, short wavelength as well as high Voc



structure of a see-through a-Si submodule

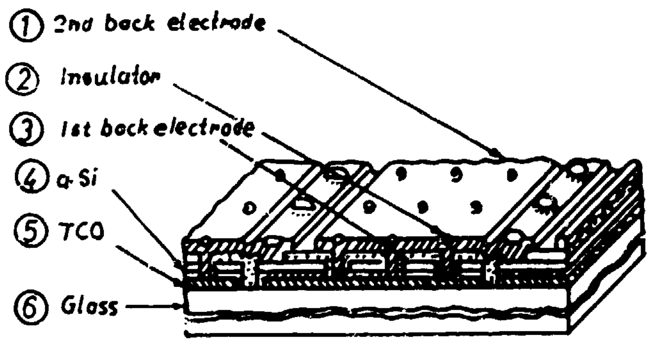


Fig.16. See-through A-Si sub module with THC type A-Si cell

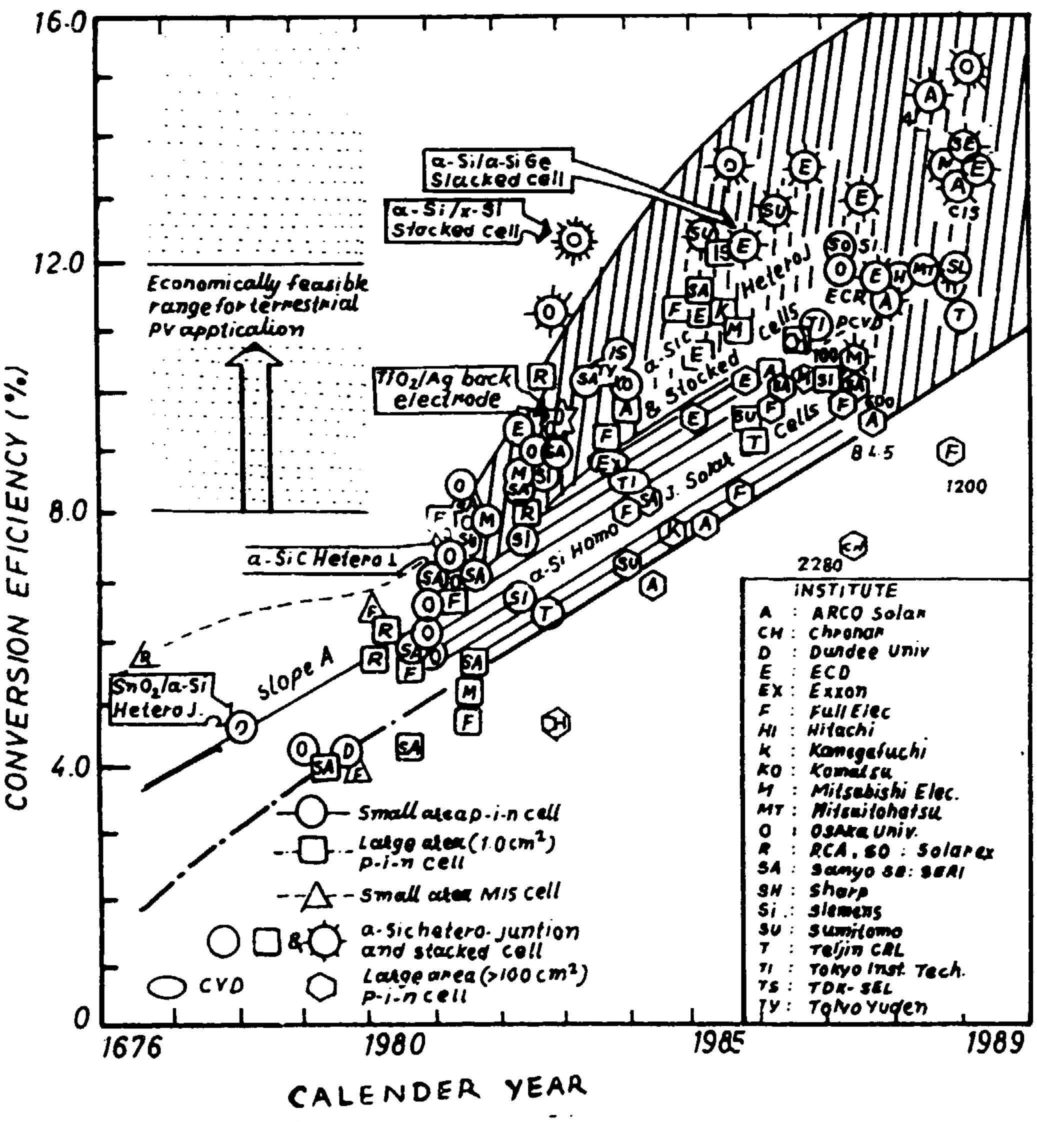


Fig.17. A-Si efficiencies for various types of cell structures. A steep rise is seen with the introduction of A-Si alloy cells.

Table 4

Performance of Single Junction Amorphous Silicon Cells

V_{oc} (Volts)	J_{sc} (MA/cm^2)	FF	Eff. %	Area (cm^2)	Organization	Description
0.967	17.7	0.703	12.0	0.03	Osaka University	SnO_2/p(a-SiC) (ECR)/i/n/Ag/glass
0.950	17.8	0.70	11.8	1.0	ECD	SS/n(μc-Si)/i(a-Si:H:F)/p(μc-Si/ITO)
0.89	17.72	0.706	11.1	NG	SHARP	Glass/TCO/p(a-SiC)BL(a-SiC)/i/n/ITO/Ag
Performance of Multijunction Amorphous Silicon Cells						
0.867	13.4	0.610	7.1	0.033	Osaka University	a-Si
0.545	23.2	0.766	9.7	0.16		Polycrystalline Si
			16.8		Total for the 4-terminal tandem	
0.880	20.5	0.499	NG	1.0	Osaka University	a-Si
0.715	10.1	0.598	NG	1.0		CdS/CdTe
			13.3		Total for the hybrid combination	
2.54	7.49	0.70	13.3**	0.249	ECD	SS/a-SiGe/a-Si/Si
1.72	9.10	0.67	10.5**	0.25	Solarex	A-SiC/a-SiGe/Glass

SS = stainless steel **SERI-verified

Critical chemical and heat treatments which are done around 420° C for 15 to 20 minutes (55,56) resulted in enhanced grain growth of thin film CdTe absorber layer thus minimizing GB effects. Achieving higher efficiencies depends mainly on materials in these cells and HgZnTe as well as CdMnTe are some of the potential candidates for increasing efficiency (57).

Thin film copper indium diselenide

Within a decade's time CIS solar cells have made rapid progress resulting in cell efficiencies in the region of 10 to 14 per cent.

The present methods used for CIS deposition include E-beam/selenization, elemental sputtering, reactive sputtering, sputtering/rapid isothermal processing among other conventional techniques. The devices are completed by depositing a thin layer of Cd S by dip coating and a layer of ZnO by MOCVD. In addition to single junction cells several four-terminal combinations such as CIS/A-Si and CIS/GaAs show promise for higher efficiencies.

Using CIS as red cell (low band gap) in combination with $CuGaSe_2$ as the blue cell (high band gap) efficiencies of 23 per cent are predicted. Summarized in table 5 are the various processes, types and efficiency etc. for both CdTe and CIS cells.

Polycrystalline silicon thin film

Astropower (58) fabricates solar cell by depositing a thin polycrystalline silicon film about 100 μm (expected to reduce to 30 μm in future) on low cost ceramic substrates. A series of design rules requiring light trapping, planar films with single crystal grains at least twice the thickness, a minority carrier diffusion length two times the thickness, benign grain boundaries, a substrate providing mechanical support and a back plane conductor are made and the entire process is amenable for low cost production. While modelling

Table 5

Performance of thin film CdTe solar cells

Type	Process	Area (cm^2)	Eff. (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	Group
Glass/TO/CdS/CdTe	Electro-deposition	0.02	14.2	23.5	819	0.74	BP Solar
Glass/TO/CdS/CdTe	CSS	1.08	13.6*	23.12	846	0.696	USF
Glass/CdS/CdTe	Screen printing	1.02	11.3	21.1	797	0.67	Matsushita
Glass/TO/CdTe	CSVT	4.0	10.5	28.1	663	0.56	ARCO Solar
Performance of Copper Indium Diselenide Solar Cells							
ZnO/CdS/CIGS/Mo/G 1	Sputter/ selenization	3.5(a)	14.1	41.0	508	0.677	SSI
ZnO/CdS/CIS/Mo/G 1	Evap	0.315(a)	12.8	41.0	453	0.69	Stuttgart, SIM, ENSCP
ZnO/CdS/CIS/Mo/G 1	E-beam/ selenization	4.0(a)	11.28*	36.75	475	0.647	ISET
ZnO/CdZnS/CIS/Mo/G 1	Evap	0.08(a)	10.5	37.8	419	0.664	Fuji

Notes: All currents normalized to 100 mW/cm^2, (a) active and (t) total area; all measurements global AM1.5

*NREL measurement

predicts efficiency in excess of 19 per cent, already at pilot production level 10.9 per cent conversion has been reported.

Advances in high efficiency solar cells and future trends

Having reviewed the current solar cell technologies we shall now look at the latest work in advances made in attaining very high efficiency cells and the developments aimed at lowering the production costs.

Table 6 summarizes some key issues of device physics for the improvement of photovoltaic performance and the suggested technical solutions (59).

A wide variety of R&D programs are in progress on each process of PV conversion with the suggested technological solutions listed in table 6.

Among these the remarkable advances have been in the technology of:

- Wide gap windows heterojunction
- Graded band profiling
- Doping
- Super lattice
- BSF treatment
- Stacked junctions with new materials such as A-Sic and c-SiC alloys.

The concept of band profiling design has been initiated as an optimum design ambipolar carrier transport in i-layer of the multi-band gap junction. As example A-SiC/A-Si/A-SiGe triple band tandem solar cell has been devised (ii) resulting in an efficiency of 15.04 per cent. Quite recently by the same combination of four terminal cell 19.1 per cent efficiency has been obtained by Ma wen *et al* (60).

Crystalline cells

PESC & BPC pushed conversion efficiencies towards 20 per cent and PERL cell technology is highly advanced technique and the novel surface structures of µ-groove, inverted pyramids (61) can promote the optical confinement and theoretical limit of short circuit current has been almost realized.

Table 6

Device physics and practical technologies for efficiency improvement of solar cells

Process and principle			Practical technologies
(A)	Better guiding of input optical energy to semiconductor and widening of special response	a-1]	Anti-reflective coating (AR)
		a-2]	Textured surface treatment
		a-3]	Increase of back surface reflection (BSR)
		a-4]	Wide gap window junction (H.J., superlattice)
		a-5]	Stacked heterogap solar cell
(B)	Efficient photo-carrier generations	b-1]	Increase of $\mu\tau$ product (film quality)
		b-2]	Decrease of surface recombination loss (HF.J)
		b-3]	Decrease of interface recombination loss (Graded J.)
(C)	Efficient generated-carrier collection (Carrier confinement and drifting)	c-1]	Drift type photovoltaic effect (p-i-n, Gradegap J.)
		c-2]	Graded impurity profile (BSF)
		c-3]	Minority carrier mirror effect (H.J)
		c-4]	Decrease voltage factor loss (H.J., HF.J.)
(D)	Decrease of series resistance loss	d-1]	Optimization of top electrode pattern
		d-2]	Tunneling injection of minority carrier (MIS)
		d-3]	Increase transparent electrode conductivity (ITO/SnO_2)
		d-4]	Integrated cascade solar cell (TF.S.C.)

If the PERL structure is made in thinner cell and FF is improved, 26 per cent efficiency may be achieved.

Multicrystalline Si cells

Key issue is the passivation of surface and grain boundaries. PESC cells using poly-si substrates (33) highest efficiency 17.8 per cent was realized on 2x2 cm area.

Thinner poly-Si cells are developed and also honeycomb reinforced structure is designed (25).

III-V Semiconductor cells

Recently Ga InP or GaAsP based cells with a suitable band gap (around 1.7 ev fitted to Si (1.12 ev)) are considered on Si cells (62). A buffer layer of Gap lattice matched with Si can be used. Conversion efficiency higher than 30 per cent is calculated using realistic material parameters in optimized cell structures.

Future trends in cell technologies

For the forthcoming generation of PV technology apart from improvement of conversion efficiency and cost reduction, emphasis would be laid on developing cell production techniques conducive to mass production.

Following are some of the technology trends in attaining high cell efficiencies:

I. Thin substrate crystalline solar cells:

(a) High-purity substrate fabrication technologies including improvement in the quality of solar grade silicon materials;

(b) High-speed substrate fabrication;

(c) New cell design and fabrication technologies including: (1) stress reduction in thin substrate cell fabrication; (2) employing optical confinement with front surface texturization and back-surface reflection; (3) surface passivation; (4) fine electrode printing and (5) large-area-cell fabrication.

II. Tandem solar cells: thin amorphous top cell with reduced photo-induced degradation combined with low cost narrow gap thin bottom cells such as:

(a) Amorphous/poly-crystaline silicon tandem cell with thickness less than 50 microns and high photo response in long wavelength region;

(b) Amorphous/compound semiconductor tandem cells with high reliability.

III. Amorphous solar cell technologies require improvements and the factors that would be emphasized are:

- High quality: narrow band gap i-layer, p-layer performance and the quality of interface film by developing new production methods;

- Large area cells: reasons for cell performance reduction with cell area increase are investigated and design technology and production process conducive to large area cells would be established;

- High reliability: light induced degradation with respect to various new materials used are investigated and stacked structure cells would be developed to realize stable cells.

- Elemental technology: complex transparent conducting films are being developed for optical loss reduction with optimizing texture and narrow band gap materials are being developed for solar cell performance by effective use of long wave length region.

The programme on super high efficiency solar cells of the sunshine project in Japan envisages development of (a) single crystalline solar cells (compound, silicon, etc.) and (b) thin film solar cells (silicon, chalcopyrite, etc.).

4. **Applications**

Solar cell technology provides a clean energy, without any moving parts, with minimal maintenance, with abundant and free fuel and also delivers power in a wide range from fractional watt to megawatts.

The first application of solar cell was in space during the 1960s followed by hand-held calculators with the advent of amorphous silicon technology and for terrestrial application with crystal silicon technology. During the beginning of the 1990s PV-powered cars have been demonstrated.

Although the initial applications of PV have been limited to remote areas, deserts, mountainous areas due to high cost of commercial electricity in these areas, the applications for household use in villages and even urban homes are increasing as the PV production costs are decreasing.

Listed here are some of the examples of PV applications indicating typical power requirements.

System	Description	Required PV Cell Output (peak power)
Lighting	Indoor lighting in villages, isolated areas, street lights, outdoor signs, tower lights, etc.	15W - 60W
Household equipment	Electrical home appliances, fluorescent lamps, refrigerators, drinking water pumps, radio, TV, etc., can be powered even in areas where commercial electricity is not available	40W - 2KW
Cathodic protection	Protecting petroleum pipelines, gas pipes and telephone cables from corrosion	500W
Land transportation control	Railway signals, unmanned railway crossings, road signs, barrier flashes and guide boards	20 to 100W
Wireless and microwave relay stations	Microwave or UHF relay stations, TV broadcast stations serving remote areas	60W to 3KW
Small clinics	Supplies lighting, refrigerator for storing medicines, powering other medical equipment especially in developing countries	300W to 1KW
Irrigation and water pumps	Irrigation pumps as well as drinking water pumps on a large scale in many developing countries	1KW - 4KW

These are some of the applications based on stand-alone systems catering to the needs of rural populations.

In view of the increasing pollution all over the world and the so-called greenhouse effect people are aware of the need to reduce CO_2 and are planning to use PV energy in urban areas as well.

In the USA, Japan, and Europe several rooftops are powered by PV for residential power requirements. Recently Sanyo company announced developing A-Si technology suitable to use on curved tiles, traditionally used in Japan. Germany has started a thousand-roof project. These are pointers for widespread PV applications even in urban locations in the near future.

Developing countries such as India, Brazil and China are increasing their PV productions to cater for their rural power requirements.

In developed countries several PV power plants in the range of 100 KW to 5 Mw exist and there are proposals for utility grid connection. Semitransparent A-SiC solar cells and see-through type solar cells have new areas of application such as sun-roofs in motor cars and decorated windows in buildings.

Solar powered air conditioner unit is yet another consumer product being produced by Sanyo (63), Japan, with a high potential market of 10 GW/year.

Contributions to global environmental issue

- Generation of hydrogen energy by electrolyzing water by PV,
- Cleaning of air pollution by ashing of pollutant gases by the glow discharge decomposition by PV,
- Stopping of desertification by PV water pumping (64),

and much anti-pollution can be operated by PV. Thus the application of solar cell ranges from powering household equipment to connection of utility grid and PV also has the potential to contribute to global environmental issues in the near future.

5. Techno-economic aspects of photovoltaic industry

The solar cell conversion efficiency data and technical milestones have been proposed by Hamakawa in 5th International PVSEC which is presented in table 7. This is based on the technical data, system lifetime production costs, production scales, etc.

The result shows a levelized cost against conventional utility power electricity cost could be accomplished by the year 2000.

US DOE has established the goal of levelized current dollar cost of $0.12/Kwh with the module cost of $1/wp (65). Japanese sunshine project also estimated separately long-term solar cell module cost target of ¥100-200/Wp which nearly coincides with US DOE goal price, taking into account the difference in electricity price.

Solar cell technologies made rapid strides specially during the last six years with several innovations in cell fabrication techniques and with the present trends the conversion efficiencies are due to reach the proposed levels. Reliability of the PV system is also becoming established. Also because PV is benign environmentally more Governments have started supporting PV applications. Japan, Germany, Italy are some of the countries which have initiated huge programmes on solar energy. Japan has revised its target of alternate energy supply and expects it would be 3 per cent of the total annual energy needs by the year 2000 and 5 per cent of the total energy by 2010 and Germany also has set similar goals for solar energy utilization.

PV module annual production is around 50 Mw cost being $4 to 5/Wp. However with mass production techniques being introduced by several industries for solar cell production and more Governments supporting solar energies and also opening up of new areas of applications for PV systems it is expected that world PV production would touch 1000 MW by the year 2000. The PV annual production is around 50 MW during 1990, PV module cost being $4 to 5/Wp.

Energy pay-back period

Energy and cost analysis studies have been made. Energy pay-back periods were as high as eight years for conventional crystalline technologies. Recently the study by Srinivas (66) on energy investments and production costs of amorphous silicon PV modules indicates energy pay-back period of frameless and single glass A-Si modules will be about 2.18 years and 1.82 years respectively, taking into account 5 to 6 per cent stabilized conversion efficiencies and an assured lifetime of over 10 years.

Cost versus production volume

Several workers including well-known PV industries, consultants and scientific bodies have calculated the cost versus production volume for modules based on A-Si technology which is shown in figure 18. With 10 per cent stabilized conversion efficiency for production volumes exceeding 100 MW the cost is expected to be lower than $1/Wp.

Economic domains for selected PV-powered applications

With the decrease of solar cell price a wide variety of applications are on the increase. Figure 19 shows electricity cost for the load-continuous 24-hour operation equivalent to the present conventional power source and 1984 PV source and forecasted electricity

Table 7

Conversion efficiency data and technical milestones

Target year		Present 1990	Near term 1995	Long term 2000
Solar cell/module efficiency (%)	Xstal-Si	18/15.5* (23.7)	20/18*	22/20
$100cm^2$ area level	Poly-Si [cast/sheet]	15.7/13.5 [15.7/12.3]	18/15.5 [18.14]	20/17.5
(Small area top data)	a-Si	10/8.7* (12.0)	12/10*	14/12
	stacked a-Si (4T/2T)	10.6/9.2 (16.8//15)	14/11	18/15
Production scale (MWP/year)		14.5	40	500
Module cost (¥/Wp)		650 ($4.5/Wp)	500* ($3.3/Wp)	100-200* ($1/Wp)
BOS cost (¥/Wp)		500 ($3.3/Wp)	350 ($2.3/Wp)	250 ($1.7/Wp)
System life (year)		20	22	25
Levelized electricity cost ($/kWh)		42** ($0.29/kWh)	27** ($0.18/kWh)	11** ($0.07/kWh)

* Sunshine project milestones.

** Module efficiency 10 per cent, annual shine period 1200hrs/year are assumed.

price at 1995 projected by Hamakawa (67) from the extrapolations of market size expansion in turn based on cost versus production volumes. This indicates large-scale photovoltaic power generation hooked up to utility grids. Feasibility studies undertaken by NEDO in Japan and DOE in USA on intermediate and large-scale operational PV systems have been successful and at present scaled up operations at a few MW levels are being planned.

Governmental and institutional promotionary role in photovoltaics all over the world

The development of PV technology in major producing countries depended on public sector support: (1) for R&D; (2) developing PV markets and; (3) creating public awareness to the new technology specially for terrestrial applications.

USA: Department of Energy (DOE) plays the main promotional role by stressing the major end usage for PV for utilities in the national programme, and through institutions such as NREL and Sandia Laboratories, carries out by coordinating and funding various programmes on R&D, standardization, advance materials technology development of solar cells, demonstration of pilot projects, BOS systems, marketing, etc., with a budget of $60 million for 1992.

Japan: Ministry of International Trade and Industry (MITI) is in charge of promoting PV as a possible source of power supply. MITI coordinates with bodies such as the Agency for Industrial Science and Technology (AIST), Electro Chemical Labs. (ETL), New Energy Development Organisation (NEDO), etc, has pursued the promotion of PV through sunshine project. The programmes are more oriented for bringing PV products to market and developing process techniques

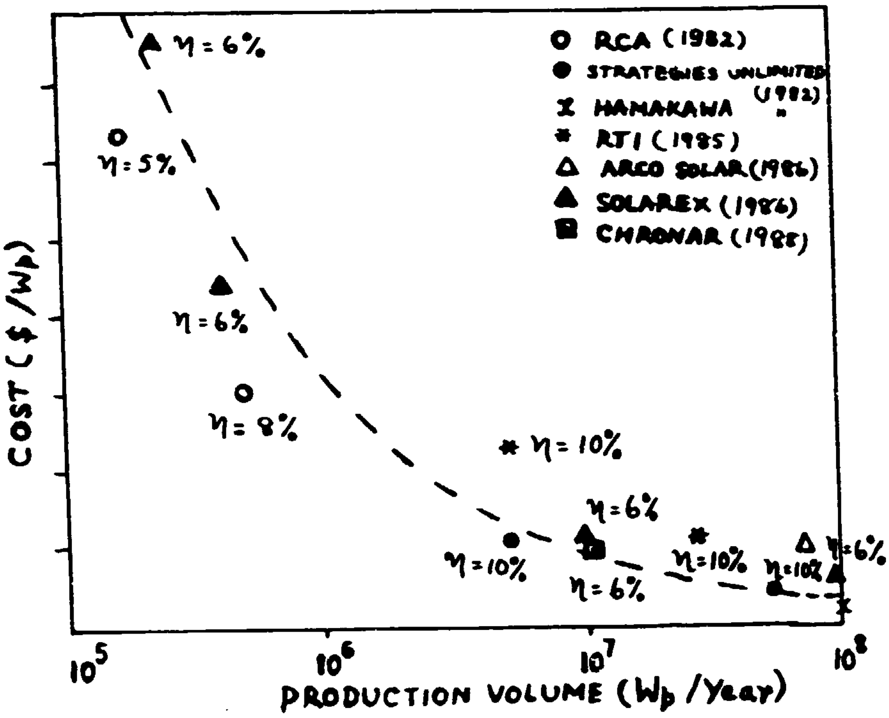


Fig.18. Prediction curve for A-Si Module cost with volume production.

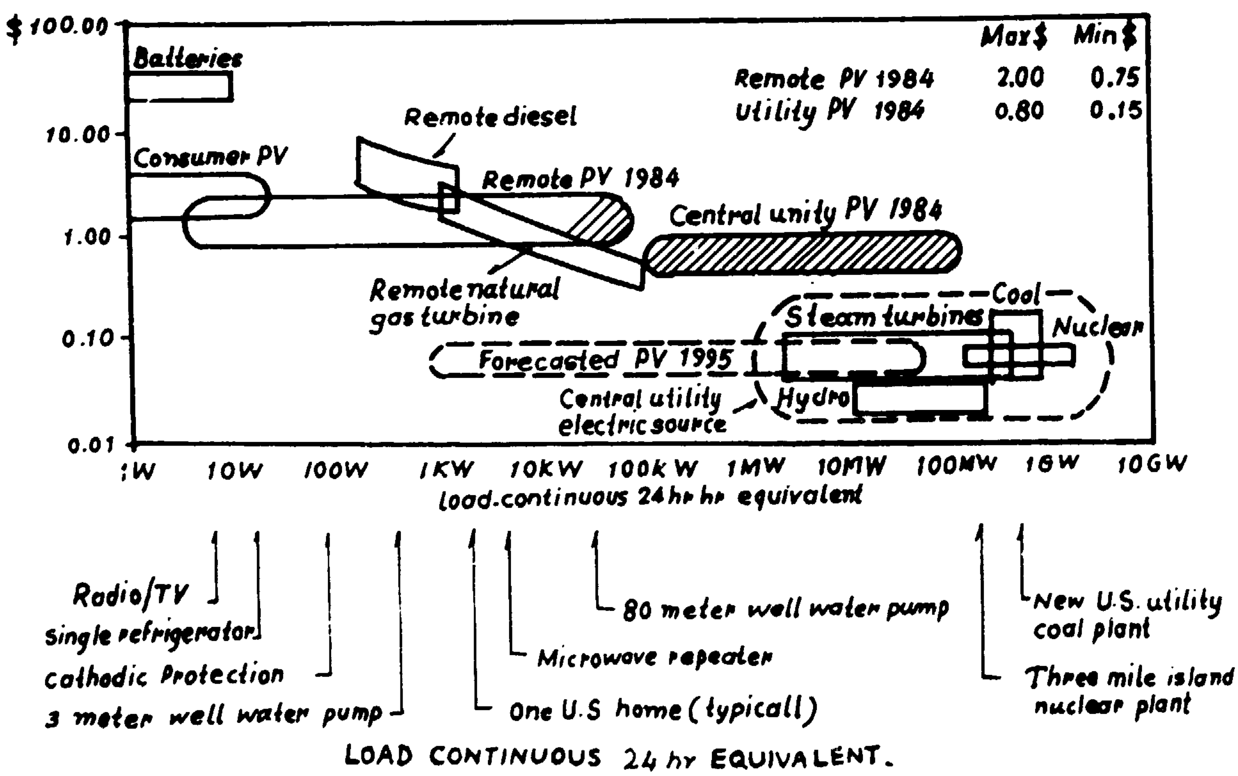


Fig.19. Economic Domains for selected PV powered applications.

conducive to mass production apart from intense efforts in bringing out new generation technologies with emphasis on quality control. Japan had a budget of about $54 million in the year 1992.

Europe: Apart from the individual country programmes in Europe they also have multinational projects such as Eureka and Joule programmes for promoting R&D as well as demonstration projects. However Germany has the biggest PV programme in Europe with a commitment to intensify PV development with several pilot projects for PV applications apart from R&D.

India: Department of Non-conventional Energy Sources (DNES) in the Ministry of Power and Non-Conventional Energy Sources is responsible for overall planning and execution of various projects in R&D, pilot projects and market assistance for PV promotion. For the five-year plan, 1992-1997, DNES has sought about $160 million for the solar energy plan.

United Nations organizations such as UNIDO, UNESCO, UNDP and several UNDP bodies have programmes in promoting PV activities.

UNIDO: The United Nations Industrial Development Organization plays an important role in forming the vital linkages between various nations for transfer of know-how and technologies from developed to developing nations and within developing nations. It has also programmes such as COSERA for promoting and augmenting solar energy applications and market surveys by providing forums for countries in various locations for interaction within countries, providing expert advice for technology promotion as well as feasibility studies for PV projects.

Because of space limitations for this report a full account of the promotional and support activities for solar cell applications pursued by several countries and United Nations bodies could not be reported.

6. Summary and conclusions

The report has reviewed the solar cell technologies, current as well as trends in the near future and shows that a new generation of technologies have emerged as a result of new innovations and advanced materials and industries are planning for mass production.

- Crystal Si is tending to show near theoretical values of conversion efficiencies with laser grooved buried contact cells and hybrid laser grooved/PERL cells;

- Multicrystalline cell efficiencies with advanced techniques reach 16 per cent and above;

- A-Si is making rapid strides with advanced solar cell structures such as tandem cells, multi-band gap stacked cells and recently by using four terminal cells achieved 19.1 per cent efficiency;

- Thin films CIS and CdTe technologies already reached 14 per cent efficiency with indication to go higher are very promising for low-cost production;

- Cell based on entirely new concept of thin polycrystalline silicon material with efficiency of about 11 per cent is highly rated to be a candidate for commercial production.

In the opinion of the author a solar cell having a thin material in the range of 20 to 30 microns be it crystalline, multi-crystalline polycrystalline material, satisfying the criteria of high efficiency cell, would be the right candidate for low-cost production.

It is also necessary that mass production techniques are adopted for further reduction of cost and making it commercially viable.

Although at present PV is catering to rural and remote areas for electrification and powering household equipment, with the use of high efficiency cells and mass production techniques PV would soon be grid connected.

Since PV is a clean energy, environmentally benign, a set of new applications could arise. It is also necessary to identify (68) PV-compatible products in each country and mass produce those items. A market survey of the present PV applications and potential application for PV would enable PV industries to mass produce those products get benefits and invest for scaled-up operations.

As described in the section entitled techno-economic aspects of PV industry further reduction of solar cell cost would bring about the desired PV market. It is expected by the turn of the century with the PV production reaching 1000 MW and cost of solar cells plummeting to ~ $1/Wp PV would be no more restricted to remote area applications but would be used for general applications including grid-connected electricity generation.

Acknowledgements

The author is grateful to many researchers from around the world; from research institutions, industries as well as government bodies, who took the time to share their latest results and information about their organizational activities for promotion of photovoltaics.

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<u>Figure captions</u>

<u>Collection of published materials on the subject - solar cell</u>

There are many journals publishing research work on solar cells. However, most of the information is published in the proceedings of three major conferences devoted to photovoltaics.

1. IEEE Photovoltaic Specialists Conference. This conference is held generally every 18 months in the USA and the proceedings are brought out for each conference.

2. European Photovoltaic Solar Energy Conference is also held every eighteen months.

3. Photovoltaic Science and Engineering Conference PVSEC, held every 18 months, venue is changed between Japan and an Asian country.

Proceedings of these three conferences form the major part of the published material on solar cell technologies, and applications.

2. TRENDS IN RESEARCH AND RECENT DEVELOPMENTS

Current directions of research on solar energy look promising

An era of wishful thinking about solar energy has been replaced by one stressing economic practicality. Nowhere is this better exemplified than at the Department of Energy's National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute, in Golden, Colorado, USA.

During past fossil fuel crises, frantic attempts sometimes were made to apply solar energy to improbable tasks. Few appreciable commercial successes were recorded, but the experience did provide a realistic perspective of the virtues and the shortcomings of solar energy.

A notable contribution from the recent past was the development of commercially important forms of photovoltaic converters. Similarly, wind-powered generators have been refined, resulting in stable designs that are useful under certain conditions. And biomass conversion is an area that could conceivably produce the greatest amount of convertible energy, but with a rather low efficiency.

Four cooperative research programmes between the National Renewable Energy Laboratory (NREL) and United States industrial firms were signed: (1) Amoco Oil Co. will cooperate in developing a process to produce ethanol from wastepaper; (2) The Advanced Battery Consortium, composed of United States automakers, will participate in developing advanced insulation for new high-performance batteries; (3) Coors Ceramics will collaborate in developing a process to make silicon carbide powders at low cost; and (4) Brush-Wellman Co. will cooperate in the manufacture of electronics components using solar energy to reduce component failure rates.

The amoco project will determine engineering and economic feasibility of converting selected feedstocks - namely, trees, grasses, and wastepaper - to ethanol via an enzymatic process that converts cellulose to sugars and the sugars to ethanol.

The Coors and the Brush-Wellman ventures will use a new high-flux solar furnace at NREL to produce silicon carbide powders and high-quality beryllium-ceramic electronic components, respectively. Coors wants to reduce imports and strengthen its overseas markets. Brush-Wellman wants to develop a reliable high-temperature solar furnace pilot plant.

Probably nothing dramatizes the utility of solar energy more than the new types of high-flux solar concentrators at the heart of the solar furnaces. There are two general designs. An imaging type forms solar images by a one-to-one mapping of the Sun and its image. Image concentrators are lenses of various sorts. The second design type is a non-imaging concentrator that collects direct solar radiation and reflects it to an absorber. The non-imaging collectors are, essentially, forms of mirrors.

The world record for concentrating solar energy is currently held by Roland Winston's research group at the University of Chicago. Winston's parabolic lens system, a form of imaging concentrator, has been able to concentrate the Sun's incident flux 84,000 times. With further system refinements, this performance may possibly be increased to 100,000 times. One of Winston's concentrators has been adopted by the NREL group in its high-flux unit for study of high-temperature chemistry and materials processing.

In September 1990, the NREL furnace recorded a concentrated solar flux of 21,000 suns using one of Winston's devices. This is a world record for a two-phase concentrator of the type at NREL. The high flux was achieved over a circular area of 1.5 cm.

These high flux rates are significant because they permit higher processing temperatures and thereby enlarge the scope of development. One reaction for which the furnace can be used is that in which silica and carbon react to form silicon carbide. An NREL test produced a material that was 80 per cent silicon carbide.

Another area of prime interest is surface modification. The very high heating rates possible with the NREL high-flux furnace permit the selective transformation of material surfaces while leaving the substrate unchanged. In a similar fashion, thin superconducting films from organometallic precursors can be laid down on surfaces. Other related processes include high-temperature self-propagating reactions, metal cladding, and phase-transformation hardening of steel alloys.

A study done at Sandia national laboratories indicates that the economics of solar furnaces could be favourable, provided they are used where there is enough light. That is one of the major problems for solar furnaces - namely, having sufficient sunlight.

For example, probably one of the most sought-after developments has been the solar pumping of lasers. So far there have been no major successes because of the low solar fluxes available. The new high-flux facility at NREL, however, may revive interest in an work on solar-pumped lasers.

Some inducement for NREL to be involved in the development of solar-pumped lasers was provided by a June 1992 study carried out by SRI International. That study concluded, among other things, that NREL's solar concentrator technology would benefit by the development of solar-pumped lasers, which would provide tunable photons over a wide range of frequencies. One prototype process that might utilize such a device would be the enrichment of uranium isotopes. The SRI study also concluded that materials processing is the most promising area for concentrated solar energy application.

Interest in solar materials processing in general is heightened by the belief that this area holds the greatest immediate promise for application of solar energy. Indeed, surface modification with a concentrated solar beam even has its own acronym: SISTM (solar-induced surface transformation of materials). The principal benefit from using solar energy is that the multiple conversions needed with fossil fuels are eliminated. Solar energy is used directly. Solar radiation can be concentrated to about 16 MW per sq. metre with single imaging concentrators and to about 190 MW per sq. metre with non-imaging concentrators in media having refractive indexes greater than one.

SISTM uses solar radiation between the wavelengths of 305 nm and 2500 nm. Concentrated sunlight impinging on the surface of a material of low thermal diffusivity can raise the surface temperature very rapidly. In the case of silicon, for example, it takes 0.414 second with an absorbed solar flux of 20 MW per sq. metre to raise the surface temperature of silica to its melting point of 1720° C.

One of the more conventional jobs that may become solar powered is the hardening of steel. Conventional heat treating requires that the object be heated to the austenite phase transition temperature and then quenched to yield a surface layer in the martensite phase region. This usually requires time, thermal energy, and expense. Selectively hardening the surface in a solar furnace may be quicker and cheaper and can also provide an object with a softer, tougher core. This developmental work is currently under way in China, the Commonwealth of Independent States, and the United States.

One of the more intriguing processes being investigated at NREL is the reactive ceramic powder surface. Certain types of refractory powder mixtures may react exothermally, and the reactions may be self-sustaining. High temperatures, sometimes as high as the melting points of some ceramics and refractory metals, are required to initiate these reactions. This technique might be used to apply new ceramic coatings to other materials.

The practical locations for solar furnaces in the United States are within the states of Colorado, Nevada, New Mexico, and Utah. The furnaces cannot operate at night or under dense cloud cover. Within these limitations, it has been shown that well-designed solar furnaces can compete with laser and arc-lamp heat sources. The economics improve as total power and the flux rise. Each reflection of the solar beam causes a loss of 5 to 10 per cent of the total power in the beam, but there are no conversion losses. The result is a 90 to 95 per cent efficiency, compared with the typical overall efficiency of 9 per cent for arc lamps and 4 per cent for carbon dioxide lasers.

A type of concentrator more familiar than the high-flux furnace is the parabolic trough collector. This type of collector could be used to decontaminate groundwater by photocatalysis. An example is a project under way at NREL that removes trichloroethylene (TCE) from groundwater.

The basic idea behind this NREL project is to immerse a semiconductor catalyst, such as titanium dioxide, in the contaminated water and then expose it to concentrated sunlight. The ultraviolet light in the solar radiation activates the catalyst to produce hydroxyl radicals, which decompose the TCE to carbon dioxide and water, with some residual hydrogen chloride.

A field demonstration of the process was made in California at Lawrence Livermore Laboratory, which had once been a naval air station. During World War II, aircraft engines were degreased with TCE, which eventually contaminated the local groundwater. The groundwater, with a relatively high concentration of TCE, was processed to concentrations acceptable to the Environmental Protection Agency.

In the field tests, groundwater was pumped to the surface, treated with the photocatalyst, and reinjected into the aquifer. The test facility treated 100,000 gallons per day at a rate of 70 gallons per minute. To avoid bicarbonate inhibition of the reaction, the groundwater was acidified to a pH of 5. Following treatment, the pH was raised to 7 by addition of sodium hydroxide. Other than mechanical removal of particulates, this was the only pre- and post-treatment required. The catalysts used in the tests were usually handled in a slurry, although packed beds of titanium dioxide pellets have also been tried. The optimum catalyst configuration has yet to be determined.

One of the problems with the type of reactor used in the groundwater studies is the space required. Up to 1.5 acres is needed for a 100,000-gallons-per-day system. The unit costs for solar installations are roughly comparable to those of more established technologies, such as activated carbon adsorption and ultraviolet-peroxide systems. Treatment costs vary from $4.50 to $11 per 1,000 gallons. Total annual costs range from $159,000 to $399,000 for a 100,000-gallons-per-day system.

NREL is aware that to successfully compete with existing technology a new method must exhibit clear economic superiority, while achieving acceptable results. The solar systems already have low power requirements and provide on-site pollution destruction. Moreover, several improvements that indicate lower future costs are under investigation.

One of the improvements is enhancement of the catalyst activity and operating lifetime. Another is development of a system that utilizes a greater portion of the solar spectrum. Further improvements that have been suggested include pre-treatment concentration of the pollutants by biological means and reduction of holding tank volume by the use of more active catalysts. This could lower equipment costs by as much as 30 per cent.

It is likely that the costs will drop with time. Projections made at NREL suggest that cost of the activated carbon systems will remain at about their present level because the systems are already mature; ultraviolet-peroxide system costs may drop slightly. NREL expects that by 1995 the photocatalytic systems clearly will be the least expensive of the three.

A similar scenario may be developing for the incineration of other hazardous wastes. Incineration usually converts toxic materials to harmless products. But the public is generally skeptical of this procedure, and that skepticism has occasionally slowed or prevented incinerators from operating. It would thus be desirable to develop an alternative that would simultaneously remove toxic contaminants from the ground and water and still be perceived by the public as being effective. NREL believes it has such an answer for at least one material - namely, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD).

EPA requires incinerators to have a removal and destruction efficiency of 99.99 per cent for most of the organic contaminants of a waste stream. For certain particularly toxic materials the destruction efficiency must be at least 99.9999 per cent. TCDD is in this latter category. Incineration of TCDD may be possible only in a limited number of operating incinerators, providing another reason to pursue the development of alternative technology. (Extracted from *C&EN*, 2 November 1992).

* * * * *

Solar cells: status and prospects

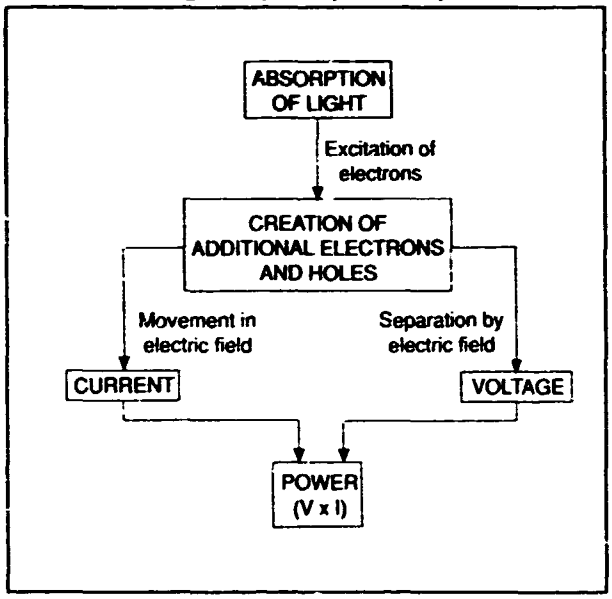
In order to maintain or improve standards of living, energy supplies are necessary, and ways must be found to minimize their environmental impacts. It has long been recognized that the renewable energies, particular energy from the sun, are much more environmentally benign than the conventional fuels in use today. However, despite this knowledge, solar energy is still not in widespread use.

Technology status

A photovoltaic cell, or solar cell as it is more commonly known, is an electronic device which produces electrical power when light falls upon it. The principle behind this is the photovoltaic effect. When light is absorbed by a semiconductor, it transfers energy to electrons in the material and, if that energy is sufficient, the electron is able to escape from the atom and move within the material. In order to use this to provide electrical power the freed electrons are made to flow through a circuit. This is done using a p-n junction within the semiconductor, which creates an electric field at the interface between the p- and n-type materials (see figure 1).

Figure 1

Schematic diagram of the operation of a solar cell



The semiconductor material used is chosen for its ability to absorb a significant amount of the incident sunlight, together with other considerations such as ease of device fabrication and stability. There are several materials which are suitable, of which the most common is silicon, as used in many electronic devices. Other useful semiconductors include gallium arsenide, cadmium telluride and copper indium diselenide.

Most commercial solar cells are crystalline silicon, for which efficiencies of between 13 and 18 per cent can be achieved, depending on the fabrication process. Present commercial thin film cells (using semiconductor films of only a few thousandths of a millimetre in thickness) are made from amorphous silicon at 5-6 per cent efficiency, but new types of cell (such as cadmium telluride) have demonstrated efficiencies in excess of 12 per cent. Cells for use in space are even more efficient, with gallium arsenide cells reaching over 19 per cent in space sunlight.

Single solar cells provide relatively small amounts of power, with a typical silicon cell of 100 cm^2 in area giving about 3A and 0.5 V in full sunlight. Since this voltage level is insufficient for most applications, several cells are usually connected together to increase the voltage. The interconnected cells form a "module", typically containing 30-36 cells connected in series (front of one cell to rear of next). At present, modules are usually designed to deliver about 15 V under reasonable sunlight conditions, since they are mostly used for battery charging. However, this is market driven rather than a fundamental requirement of the technology. The module also provides mechanical strength and protection from environmental attacks from moisture or atmospheric pollutants, giving an expected module lifetime in excess of 20 years. A typical module will give a power output of 30-50 W under good sunlight conditions.

When more power is required, a number of modules can be connected together to form an "array". The array produces direct current electricity, rather than the alternating current electricity generated conventionally, so an inverter must be used to power ac loads. Provision must also be made for the variability of the supply, usually by including storage facilities (for example batteries) in the system. Alternatively, a hybrid system can be used where some other electricity supply technology (perhaps wind or diesel generation) is used when solar electricity is not available. Since the solar array has no moving parts, it requires little maintenance other than occasional cleaning and provides a high level of reliability.

Research activities

The main challenge for the photovoltaics industry remains the reduction of electricity production costs, and most of the research activity is related to this requirement in some way. Considerable effort is being expended on system technology, including the electrical and structural elements, and on efficient ways of integrating the photovoltaic system with other electricity supplies, including the conventional grid supply. However, space does not allow a full discussion here and this section will concentrate on developments in cell and module technology.

The cost of electricity produced from a solar module can be reduced in one of two ways: by increasing the efficiency (more power is obtained for the same cost) or by reducing the production cost of the module (the same power is obtained for less cost).

Increasing efficiency: Most of the commercially available photovoltaic modules, based on crystalline silicon solar cells, use cell fabrication technology which was originally devised in the late 1970s. Refinement of the techniques has allowed efficiencies of up to 15 per cent to be reached but production efficiencies are more commonly in the 12-13 per cent range. In the research laboratories, higher efficiencies have been reached (see figure 2). Over the past few years, some major advances have been made in the design of the crystalline silicon cell, most notably by the group at the University of New South Wales led by Professor Martin Green. The inclusion of refinements such as laser grooved buried contacts, passivation of both front and rear cell surfaces and the reduction of contact area on the rear of the cell has led to cells in excess of 23 per cent in efficiency. Figure 3 shows a schematic diagram of one of the advanced cell designs.

It may take up to ten years to transfer technology developed in the research laboratories into commercial production. However, the buried contact process has already been adopted by some leading European module manufacturers, including BP Solar. By burying the grid lines of the top contact to the cell, the amount of the cell area shadowed by the metallization can be reduced substantially without decreasing the cross-sectional area of the grid line and hence increasing its electrical resistance. It has been shown that this can raise the efficiency of a cell by about a third. BP Solar have produced cells up to 18 per cent in efficiency, leading to module efficiencies of around 16 per cent.

The single junction cell, however, has a fundamental limitation on its efficiency since it can only absorb part of the incident light spectrum. Increases in efficiency can be obtained by stacking cells on top of one another, each one responding to a different part of the spectrum, and this is called a multijunction cell. Figure 4 shows a schematic diagram of a two junction cell made from a gallium indium phosphide ($GaInP_2$) top cell and a gallium arsenide (GaAs) bottom cell, which has reached over 27 per cent efficiency. Multijunction cells can be designed with subcells from a number of different III-V semiconductor compounds, with three cell systems generally considered to be the practical limit. Many of the cells are designed to be used with concentrated sunlight, and efficiencies over 30 per cent have been measured for a number of cell designs. At present, these cells are still very small in area and the materials and fabrication techniques are expensive. Although commercial manufacture may be some way off, they hold a promise of high efficiency for the future.

Reduction of production costs: In addition to improving efficiency, it is possible to reduce the resultant electricity cost by reducing the module's production costs. Indeed, this will be necessary if widespread cost effectiveness is to be achieved, even with the efficiency developments discussed above. Figure 5 shows the reduction in module cost over recent years, most of which has come as a result of improved production techniques, such as process yield, and increases in the production capacity of the manufacturing facilities.

Significant cost reductions are predicted for the thin film modules when compared with crystalline silicon. This results from a number of factors, including

Figure 2

Graph of efficiency increases since 1978 for several solar cell types. Module efficiencies are usually 1-2 per cent lower than cell efficiencies, because of area and mismatch losses

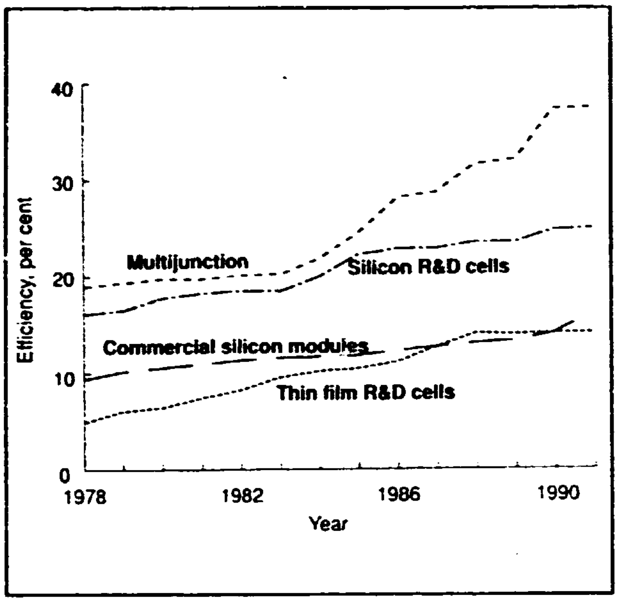


Figure 3

The buried contact solar cell developed at the University of New South Wales

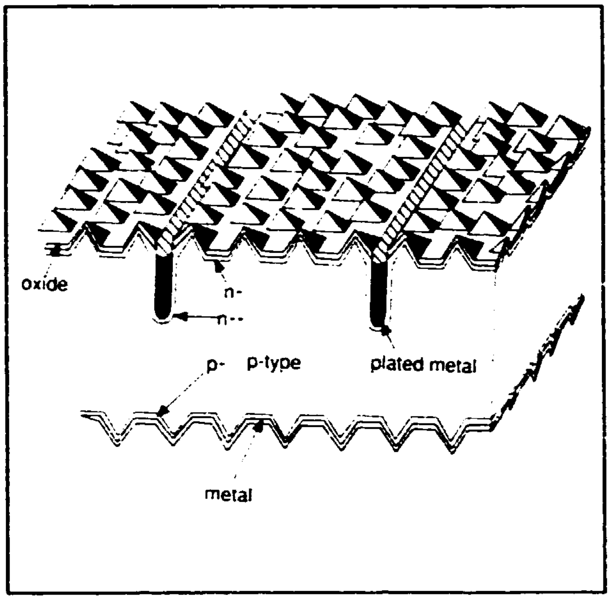


Figure 4

Schematic cross section of the GaInP₂ / GaAs two terminal tunnel junction interconnected tandem cell developed at the National Renewable Energy Laboratory, Colorado

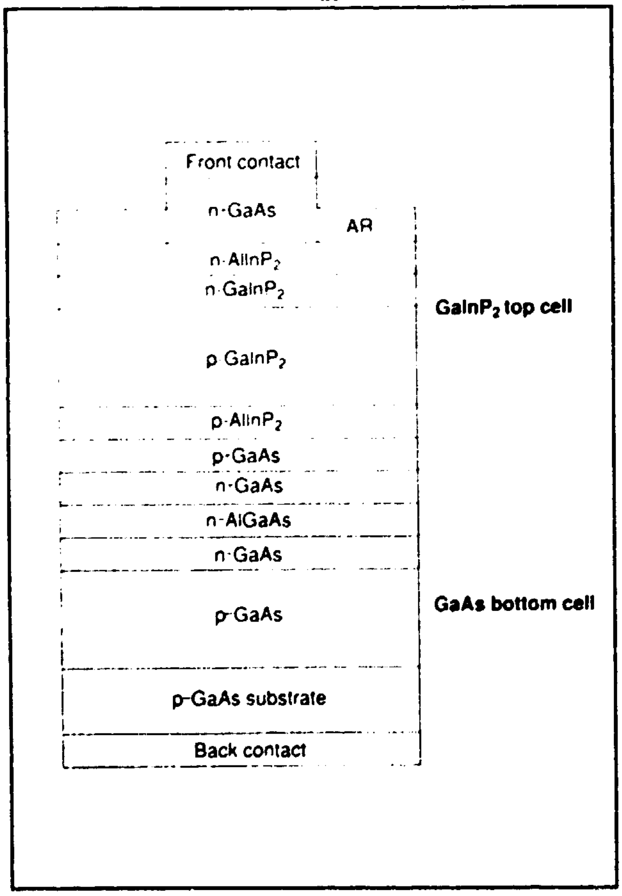
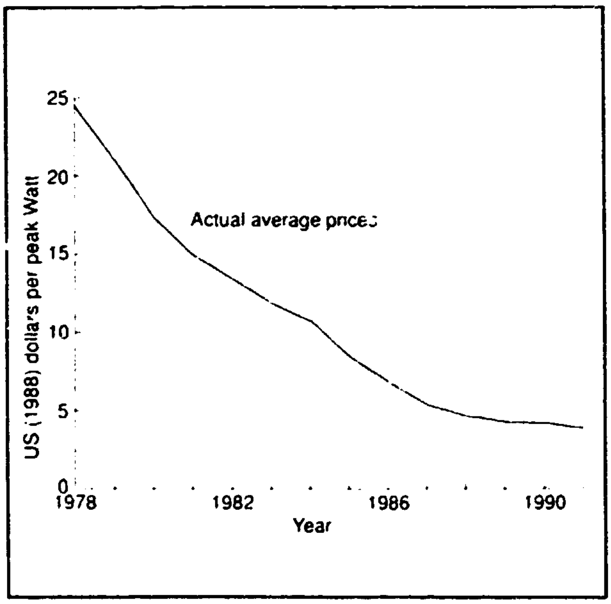


Figure 5

Reductions in photovoltaic module costs since 1978.



the reduction in the amount of material required (a few microns of semiconductor film, rather than 300-400 microns of crystal) and the prospects of large-scale automation. The most advanced thin film cell, in a commercial sense, is amorphous silicon. However, this has some stability problems and may not be suitable for use in power applications greater than a few tens of watts. Most of the research activity in thin film cells is targeted on II-VI and related compounds, such as cadmium telluride and copper indium diselenide. These cells are close to commercial production, although there is still work to be carried out on large area uniformity and process yield. The concept of multijunction systems can also be applied successfully to thin film cells and this promises to improve module efficiency without a significant penalty in cost.

Cost reductions can confidently be predicted for all commercial cell technologies as a result of an increase in production volume, in common with most industries. To date, the photovoltaic industry is small, with annual production world wide in the order of 60 MW or so. The potential growth of the market over the next decade should see a consequent reduction in module costs, as larger and more economical production facilities are installed.

Environmental impact

All energy supply technologies have an environmental impact of some type and, if we wish to aim for a sustainable environment, these must be accounted for in some way. Ideally, a cradle-to-grave approach should be adopted. It is usual to consider four stages: construction and commissioning of the generating equipment; fuel extraction and supply; operation; and decommissioning and disposal at end of life, including any recycling.

The construction stage includes the manufacture of the solar modules, support structures and electrical components, together with transportation to the site and installation. The environmental impacts come from the materials (especially chemicals) used in manufacture and from the energy input to the production process. It is important to develop fabrication processes which minimize the use of toxic materials and to adopt environmentally safe practices at all stages.

If it is assumed that the required energy is provided by the present conventional technologies, then an associated environmental impact can be determined. For example, it has been calculated that the production of thin film solar modules would result in less than one-thirtieth of the carbon dioxide levels of conventional generation, for sites of reasonable insolation levels. Interestingly, as the proportion of electricity generated from renewable energy technologies increases, effective carbon dioxide and other gaseous emissions would decrease, since they arise only from the energy input to manufacture.

Solar electricity requires no fuel in the conventional sense. Thus, there is no environmental impact from the processing or transportation of fuels. This can be compared with the effects of coal mining, oil extraction (including the risk of contamination by spillages) and reprocessing and disposal of nuclear fuels. It also has little environmental impact in operation. There are no gaseous emissions and no noise. Some would argue that there is visual intrusion resulting from the siting of the modules, but this is mainly a matter of taste. Indeed, it should be possible to enhance the appearance of many buildings by the appropriate use of solar modules.

The fourth category relates to the disposal of the generating plant and the return of the site to its previous condition. Many of a solar plant's components, including the modules, should be capable of substantial levels of recycling. The development of appropriate recycling practices is one of the challenges facing the photovoltaics industry as the production volume expands. The disposal of a solar electricity generation plant would, therefore, appear to have lower impacts than a conventional plant. This is particularly true of nuclear plants, for which decommissioning procedures and costs remain unknown.

The quantification of environmental impacts is a complex procedure and it has only been possible to give a brief outline for solar power. However, it seems clear that the impacts will be substantially less than for conventional energy supply technologies.

The future

The production of energy from the sun seems to have been promised for many years without making a significant impact on world energy supplies. In fact, photovoltaics has only been widely studied for terrestrial applications for about 20 years. Before that, it was used almost exclusively for powering satellites in space because of the twin advantages of low weight and no fuel requirements. Indeed, almost all of today's satellites still obtain their electrical power from solar cells, although these are significantly more efficient than their earlier counterparts.

The stimulus for developing solar electricity for use on Earth came from the oil crises of the 1970s, and the advances in efficiency and cost effectiveness since then have been discussed earlier. For a new technology to make a significant impact on the energy market in only 20 years would be remarkable indeed, if only in terms of the lead times for the installation of the required production capacity. So, even though it is not here now, we can confidently predict that photovoltaics will be in widespread use shortly after the turn of the century.

If this is so, where and how will solar electricity be generated and used in the year 2020? In theory, the electricity from solar cells can be used in any of the applications where conventional electricity is used now, but there are some instances where the characteristics of solar electricity make it particularly attractive. Two of the main options, covering both the industrialized and the developing countries, will be highlighted here.

Photovoltaics is a particularly attractive technology for remote power applications, because of its reliability, low maintenance requirements and zero fuel needs. Thus, it has tremendous potential for widespread use in bringing electricity to villages and towns in developing countries, for uses such as pumping water, lighting, refrigeration, communications and for small industry. The provision of even small amounts of power can transform health care and education standards and begin to reverse the trends of migration towards the major cities - a factor closely linked with an increase in poverty. Solar power also has a major role to play in these countries in providing a more reliable electricity supply in the towns and cities. It is to be hoped that by 2020, a significant fraction of the non-electrified villages in Africa, the Indian subcontinent and South America can be provided with solar electricity leading to improved productivity and standards of living.

In the industrialized countries, solar electricity can be expected to make an increasing 'contribution to the energy demand, although not necessarily in the form of large solar power plants. In the past two or three years, researchers in several countries have begun to investigate the possibility of mounting photovoltaic modules on existing building structures such as office blocks and domestic houses. Otherwise unused areas of building facades and roofs would be generating electrical power, which would often be used within the building itself, thus eliminating distribution costs. Since photovoltaic modules produce no emissions or noise in operation, this would not affect the inhabitants of the building in any way.

Although the electricity costs from building-mounted systems will not compete now, predictions suggest that, even in the relatively unfavourable solar climate of the United Kingdom, such systems could be cost effective within the next 15 years.

Solar modules mounted on building roofs or walls are likely to become a familiar sight. Panels will also be widely used for power for road signs, advertising hoardings and a wide range of consumer products. Electricity supply utilities are already starting to evaluate the use of photovoltaics in embedded generation, where a small plant is installed at the end of a distribution line to supplement and improve the quality of the delivered power. In places where there are large desert regions of low land price, solar plants will be installed to meet peak power loads, whereas in areas of higher land price, these loads will be met by modules on individual houses.

Photovoltaics, the direct conversion of sunlight to electricity, is still a very new technology compared to other energy supply technologies, but it is clear that there is considerable scope for the achievement of high conversion efficiencies and for cost reductions that will lead to economic competitiveness on a wide scale over the next 30 years. Sunlight is an abundant energy source, although there remains the technical challenge of coping with the variability. However, the low environmental impacts and inexhaustibility of sunlight mean that solar electricity can make an important contribution to an energy supply which is truly sustainable.

(Dr. Pearsall, the author of this article, is at the Newcastle Photovoltaics Application Centre, University of Northumbria, Ellison Place, Newcastle upon Tyne NE1 8ST, UK). (Source: *Chemistry & Industry*, 18 January 1993)

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<u>Photovoltaics</u>

Photovoltaics - turning sunlight into electricity - is a technology that is only beginning to be tapped. Current applications for solar cells fall into two major categories: cells as self-enclosed energy sources for appliances like pocket calculators and outdoor lighting, and cells that provide utility-company electricity for homes and other large users, often configured in grids. Except for silicon photovoltaic elements, appliance cells tend to be all-plastics.

Manufacturers of photovoltaic (PV) cells say that the real growth potential is in the utility category, provided that the costs of producing the cells can be brought down, in turn reducing the cost-per-kilowatt of solar electricity. While more efficient silicon PV materials within the cell are the key to reaching this goal, manufacturers agree that plastics lenses, frames and encapsulations will help make this possible. Materials that are clear, tough and weatherable, such as polymethyl methacrylate (PMMA) and ethylene-vinyl acetate (EVA), are already playing roles in this technology.

Peak power electricity created from conventional coal-powered sources typically costs around 5c/kilowatt hour, whereas electricity produced with state-of-the-art PV technology costs 20-30c/kWh. Most research is now centred on "thin film" cells, where amorphous silicon is coated onto an inexpensive substrate web of stainless steel, glass, or plastics. Although thin film cells are less efficient than those made of crystalline silicon (typically converting 6 per cent and 20 per cent of the light into energy, respectively), they can be manufactured in continuous hydrogen deposition processes at low cost.

New PV materials, such as copper indium diselenide, cadmium telluride, and silicon germanium that can also be applied as coatings, could further increase performance. Other research is testing the feasibility of crystalline silicon as a coating, which could reduce its manufacturing costs.

Companies manufacturing and developing PV technology still have a long road to profitability, however, as they attempt to overcome technical obstacles to entering the commodity electricity market. Government assistance is necessary for their survival. For the first time, firms developing PV solar cells in both Japan and Germany receive more government assistance than those in the United States, a significant factor in those two countries assuming a leadership role with this technology. The United States Department of Energy has increased its spending on PV research, from $36 million in 1990 to $46 million in 1991, but that is a far cry from the $155 million it spent in 1981.

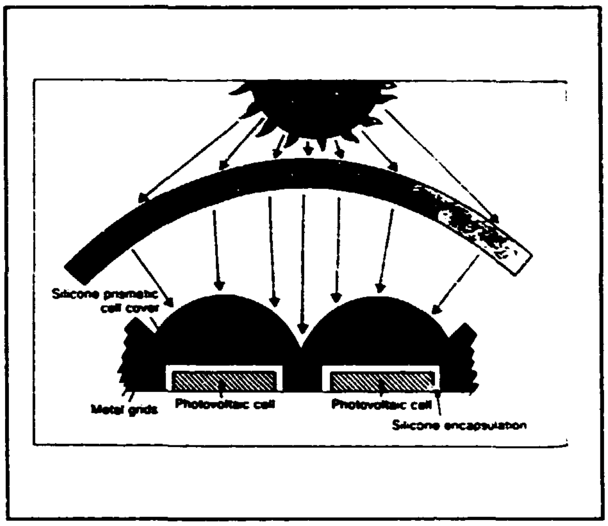
Private industry, too has been more patient with PV technology in Japan and Germany, where companies seem more willing to assume consistent losses with a promising technology. Examples include Arco selling its Arco Solar subsidiary, a major producer of amorphous silicon cells based in Camarillo, CA, USA, to Siemens AG, Munich, Germany, in 1989 (the company is now called Siemens Solar Industries). And Energy Conversion Devices, Troy, MI, USA, sold 50 per cent of its subsidiary Sovonics Solar Systems to the Canon Corp., Tokyo, Japan. The joint venture is called United Solar Systems Corp.

<u>Plastics funnel light, cut costs, add protection</u>

Plastics play a corollary role in the search for more efficient PV electricity, allowing for better deployment and manufacture of the cells themselves. One primary example of this is clear prismatic lenses used to cover grids of PV cells. The lenses funnel the sun's rays towards the cells, providing them with more light from a larger area. By concentrating the light into a smaller area, the area of silicon cells needed to produce a given amount of electricity is reduced - essentially a substitution of plastic lens for silicon. When one considers that silicon cells cost approximately $\$5.50/m^2$, while the cost of optical-grade PMMA sheet is around $40c/m^2$, it is easy to see the attractiveness of such a substitution. The silicon cells represent approximately 80 per cent of the cost of a PV electricity source.

A firm that has pioneered the lens approach is Entech Inc., with a configuration that features a Fresnel lens of PMMA, made to its specifications by 3M, St. Paul, MN, USA. Although 3M's production process is proprietary, the PMMA contains thousands of triangular prisms that redirect light.

Another feature of the Entech system is a silicon lens cover, which uses essentially the same Fresnel lens technology to direct sunlight away from metal grids that separate the PV cells, and towards the silicon (see diagram). These metal grids would otherwise absorb 25 per cent of the available sunlight. Entech has installed one such system at the 3M Research Center in Austin, TX, USA.



Prismatic plastics lenses funnel sunlight to photovoltaic cells, increasing efficiency of electricity production. [Illus., Entech, Ins.]

As for PV cells themselves, various plastics are used as encapsulations, backings, and frames. The encapsulation faces the sun and must be transparent as well as tough, but the backings and frames need not be clear. Sources at Siemens say its thin film cells are encapsulated in ethylene-vinyl acetate, then provided with a polyvinyl fluoride/aluminium laminate backing. According to Siemens, most amorphous and polycrystalline cells are encapsulated in EVA because of its resistance to moisture and delamination.

Cell manufacturer Solarex encapsulates its polycrystalline cells in EVA, then provides a backing of Tedlar PVF from Du Pont, Geneva, Switzerland, in a vacuum lamination process at around 150° C. For its thin film cells, which are a few metres square, the company injection moulds frames of Lexan polycarbonate from GE's Plastics Division, Pittsfield, MA, USA. Polycarbonate had been chosen because it has been environmentally proved. This is important for outdoor commodity electricity applications.

Speeding manufacturing in order to make PV cells less expensive is another tactic taken by some cell makers. One way of accomplishing this is to deposit the silicon onto either side of an inexpensive, flexible polymeric substrate roll before encapsulation.

Two companies producing lightweight solar-cell banks in this way are Sanyo Corp., Tokyo, and United Solar Systems Corp., Troy, MI, USA. USSC uses substrate rolls of Kapton polyimide film from Du Pont.

The material withstands the 300° C deposition process without degassing or decomposition. (Extracted from *Modern Plastics International*, June 1991)

* * * * *

Solar Power Satellite (SPS) R&D and international cooperation

A. Sunshine Project and Solar Power Satellite

1. Sunshine Project and Global Environment Preservation

The Sunshine Project to develop technologies for alternative energy resources to replace petroleum was started in 1974 as a National Project of the Agency of Industrial Science and Technology, MITI. Since then, researches have been continued to develop energy resources technologies such as photovoltaic power generation, geothermal power generation, coal liquefaction and gasification, and use of hydrogen energy.

However, 16 years after the Project was started, a change occurred in the Project's basic policy. Because of the urgency in coping with global environmental issues and the present situation surrounding energy research and development that necessitates the development of innovative technologies over a long-term perspective, it was decided that the present energy resources diversification objective would be expanded by starting long-term R&D projects extending beyond the year 2000 to help resolve global environment issues through the development of innovative clean energy resources.

The R&D themes adopted by the Sunshine Project were reassessed, the present research themes were coordinated and several new themes were added (figure 1).

One new theme is solar power satellite technology research, a long-term R&D theme extending beyond the year 2020, which will be part of activities to develop solar energy technologies.

2. Outline of Solar Power Satellite (SPS)

The solar power satellite uses a massive artificial satellite incorporating a large photovoltaic power generation system in geostationary orbit. The enormous power generated is converted into microwaves and transmitted to the Earth where the microwaves are received with an earth antenna and reconverted into electricity.

By using photovoltaic power generation technology in outer space the problem of interference by weather, which frequently impedes the use of solar energy, would be eliminated, so by using several satellites and several earth power-receiving stations in combination, power could be supplied from outer space to the Earth around the clock.

The Department of Energy (DOE) and NASA in the United States conducted a joint feasibility study in 1977-1979. This study assumed a photovoltaic power generation satellite equipped with a massive solar cell panel 10 km long and 5 km wide, and a power generation capacity of 5,000,000 kW (figure 2). Various problems were identified in the "environment", "economy" and "society" when 60 sets of these SPS were launched into outer space to meet the power demands of the entire country.

3. R&D of Solar Power Satellite in Sunshine Project

In the Sunshine Project, research study commenced in Fiscal Year 1991 on SPS as a futuristic system for solar energy utilization. This restudied the feasibility of the country's present energy system, to evaluate the influences of SPS on the Earth's environment, and to restudy SPS's feasibility once more by taking into account the changes which have occurred in the energy situation, ten years after the SPS study conducted by DOE and NASA. A research study committee was established under the leadership of NEDO (New Energy and Industrial Technology Development Organization), and several working groups under the committee studied various themes independently. The contents of these studies during Fiscal Year 1991 were:

(a) Survey of present SPS R&D in Japan and other countries

- **Trends of R&D in Japan and other countries**

A survey will be conducted on trends of SPS R&D in Japan and other countries, to elucidate the system characteristics and problems involved.

- **Study of technological development**

Studies will assess the existing and future possibilities of SPS's main elements.

(b) Evaluation of SPS economy

Studies will evaluate SPS economy such as energy balance and power generation cost.

(c) Survey of SPS influence on environmental and ecological systems

Studies will assess the influences of microwave power transmission on environmental and ecological systems such as the ionosphere, humans and communications.

To conduct these surveys in detail, working groups have been established for evaluating power

Figure 1

Middle and long-term plan for new energy technology development

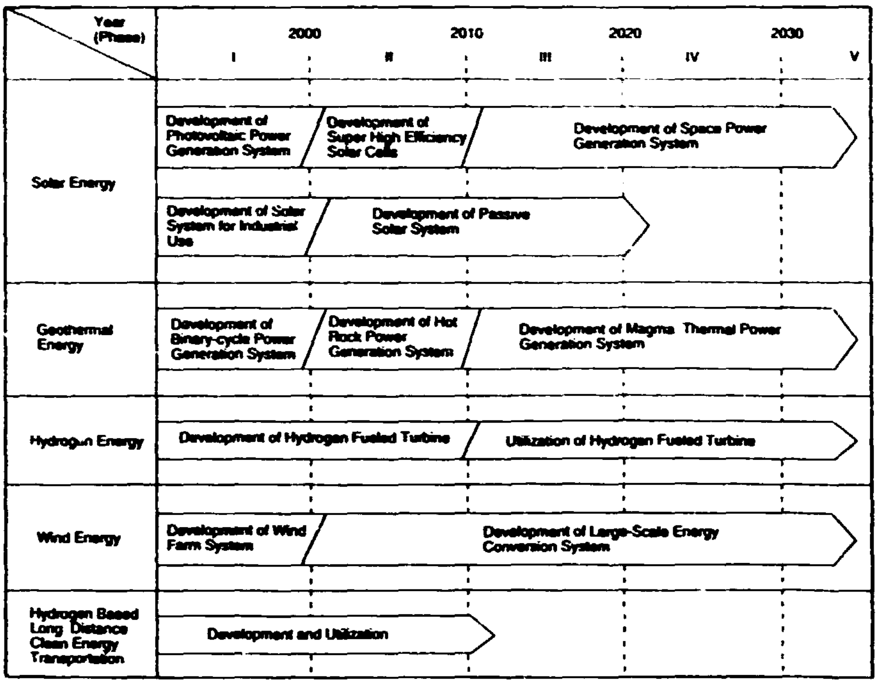
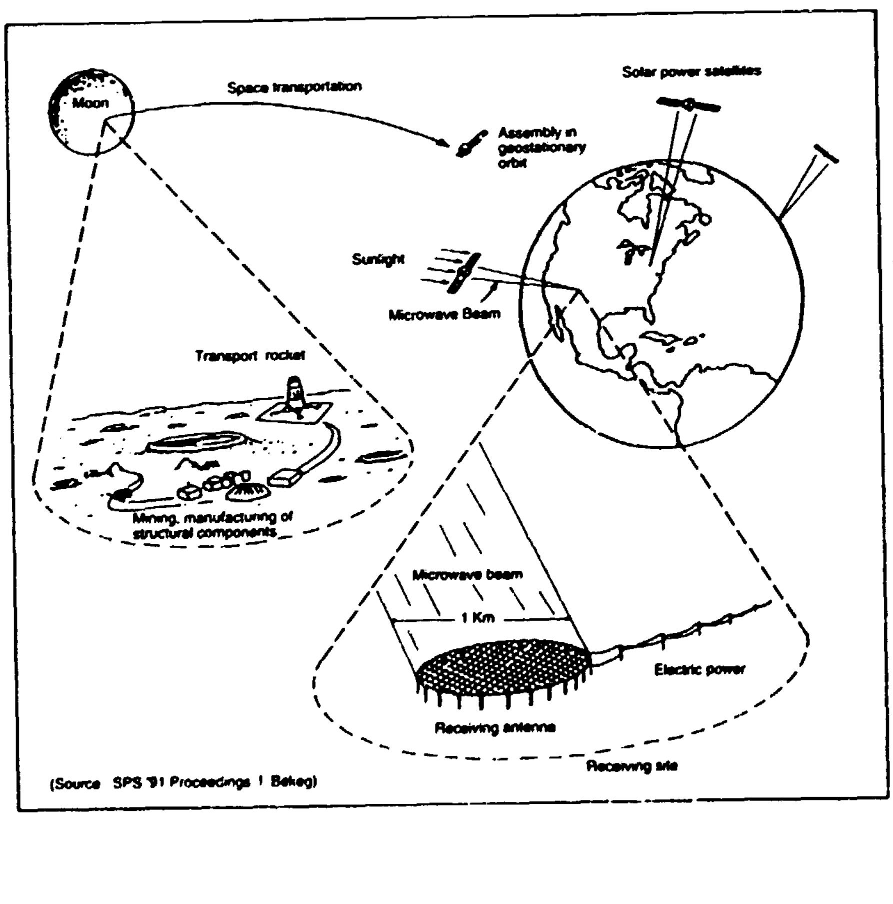


Figure 2.

Concept of solar power satellites



generation technologies, system economy, environmental influences and ancillary infrastructures.

B. SPS '91 and international cooperation

The symposium "SPS '91" with SPS as the main theme was held near Paris, France, in August 1991, under the sponsorship of the Society of Electricity and Electronics (SEE) and the Society of Science and Technology (ISF) of France. This was the second such symposium and was held five years after the first SPS '86. The gathering included Dr. Glaser, the proposer of SPS, and numerous active participants in this field.

The symposium's scale was definitely much larger than the preceding event, with more than 200 researchers and government representatives from 20 countries. Previously, the principal participants were working in space development, but this time the seminar was characterized by many researchers in other fields such as energy, nuclear fusion, environment and macroengineering. There were 104 lectures and a poster session. Themes extended over a broad cross-section of SPS including SPS demonstration plans, research on basic technologies, energy and environment on a global scale, and nuclear fusion using helium on the moon (figure 2).

On the final day, a round-table conference was held on international cooperation, and many opinions voiced on the trends of SPS R&D as well as the importance of international cooperation. An American private enterprise researcher suggested that the outlines of international cooperation on SPS research should be decided immediately.

In fact, the SPS is a massive, ambitious undertaking involving many formidable technical problems such as how to build the massive structure and how to transport it into outer space. These matters cannot be solved by a single country due to the lack of researchers and funds. In addition, the benefits of SPS commercialization should be enjoyed by all countries, and not only by Japan or any other single country. Therefore, research on SPS should be advanced from the initial stage under close liaison and cooperation among SPS and energy researchers world wide. (Source: *JETRO*, 1991)

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A new kind of photovoltaic cell

Two scientists working at the Swiss Federal Institute of Technology have developed a new kind of photovoltaic cell that uses some of the principles used by chlorophyll in green plants to convert solar energy into chemical energy. This cell converts solar energy more efficiently to electricity than plants. The photovoltaic cell would be cheaper to produce than the cheapest of current amorphous or noncrystalline, silicon photovoltaic cells. Diffused sunlight is converted into electric current 12 per cent more efficiently. A thin layer of liquid electrolyte is enclosed in the cell and the edges glued together. Microscopic molecular antennas, which are a key innovation to the new cell, are used to collect sunlight. (Excerpted from *New York Times*, 24 October 1991)

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New surface coating for solar collectors

Two Australian physicists from the University of Sydney say they have developed a surface coating for solar thermal collectors that converts 98 per cent of the incident sunlight into heat. They also have designed a new solar collection device using the multi-layer coating.

The high-efficiency selective surface (HESS) is composed of four layers of metals, ceramic-metal alloys known as "cermets", and insulating materials. The layers are very efficient in absorbing high-energy solar radiation and restrict the re-emission of low-energy infrared radiation, resulting in a heat loss three to five times less than that from existing thermal surfaces, the developers say. HESS also can operate at a wider temperature range (room temperature to 500° C) than current thermal surfaces.

The two physicists have designed a new solar heat collector to take advantage of the HESS coating. The collector converts 20 per cent of the sunlight that falls on it into electricity, which makes it potentially competitive with conventional power plants.

The collector is based on two concentric glass cylinders with a vacuum between them. A trough-shaped reflector concentrates sunlight onto the collector tubes. The HESS coating is deposited on the outside surface of the inner cylinder, creating an arrangement much like a Thermos bottle. A stainless steel tube inside both glass cylinders contains purified water boiled by the heat. A heat exchanger transfers heat from the boiling water to a steam turbine.

The entire device measures about 2 x 2 metres. Because the device is so small, it can be oriented to capture about 10 per cent more sunlight than commercially available systems. The two physicists estimate that their system could be used in large power grids and factories to generate electricity at 4 cents per kilowatt hour, compared to the 5 to 6 cents per kilowatt hour cost for conventional coal and nuclear plants. (Excerpted from *Int'l Solar Energy Intelligence Report*, 13 December 1991)

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Amorphous solar cell with 11.1 per cent conversion efficiency

Sanyo Electric Co., Ltd. has developed an amorphous solar cell with the world's highest conversion efficiency under commission from the New Energy Industrial Technology Development Organization (NEDO). This cell is 100 cm^2 and attained a conversion efficiency of 11.1 per cent, previously 10.6 per cent.

This integrated type cell mounts 14 amorphous solar cells in series on a 100 cm^2 glass board. Development may allow the NEDO target of a 12 per cent conversion efficiency to be achieved. Quality improvement of the amorphous film, the most vital factor for conversion efficiency improvement, has already been achieved by i-layer quality improvement using the superchamber system in an ultra-high vacuum (UHV) and quality improvement of the p-type SiC film using trimethyl boron as the dopant.

The new cell, in addition to a high quality interface layer between the p- and i-layers, has a new ultra-thin i/n interface layer formed by hydrogen radical treatment, so carrier recombination losses on the i/n interface were suppressed and the fill factor (FF) improved.

Patterning of the integrated type amorphous solar cell has already been optimized by the thermal analysis simulation method, but a new laser patterning technique called Ablation Oriented Laser Patterning (ALOP) process was developed requiring minimum heating processes. Therefore, high-accuracy, low-loss processing is possible without fusion droops compared with the conventional thermal processing based on the fusion deposition method, so both the output current (Isc) and fill factor (FF) have been improved. (Sanyo Electric Co., Ltd., Corporate Communication Dept., 1-1-10, Ueno, Taito-ku, Tokyo 110. Tel.: +81-3-3837-6206, Fax: +81-3-3837-6381). (Source: *JETRO*, January 1992)

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Amorphous solar cell with polyester film substrate

Teijin Ltd. has developed technology for integrated mass production of amorphous silicon solar cells consisting of a polyester film substrate with a thickness of 100 μm (total 200 μm including the coated parts). The mass-production size is 20 x 60 cm, but it is technically possible to produce cells with a thickness of 50 μm or in sizes over 1 m^2, the manufacturing size of PET films.

The new solar cell is an extra-thin, lightweight version with less than 1/30 the weight, and less than 1/10 the thickness of conventional silicon substrate solar cells. In addition, the cell uses the PET film characteristics of high flexibility and resistance to cracking, so has a broad range of applications.

In the conventional solar cell mass production method, aluminium-tin electrodes are first formed by the sputtering process on the surface of a dimensionally stable film at high temperatures. On these electrodes amorphous silicon films are coated by the glow discharge process. Transparent electrodes (indium-tin oxide) are formed by the sputtering process, produced in a laminated modular structure by screen printing and laser treatment, then coated with PET film laminate for surface protection. The company has integrated all these processes.

The energy conversion efficiency of the mass-produced solar cell is maximum 6.3 per cent and average 5.4 per cent (yield of over 90 per cent), and roughly 7 W of electricity is generated. The cell has a durability comparable to or better than silicon substrate types, does not crack and has excellent flexure with a 10-mm radius of curvature. The width is restricted by the PET film manufacturing facility, but the length can be extended as desired, so it can be cut into required sizes.

The company had participated in the project from 1980 to 1988 as part of the Sunshine Project of the Ministry of International Trade and Industry, and engaged in research to manufacture solar cells other than those using silicon substrates. As a result, it has established a mass production technique based on the roll-to-roll process using PET film as the substrate. (Teijin Limited, Public Relations Section, 2-1-1, Uchisaiwai-cho, Chiyoda-ku, Tokyo 100. Tel.: +81-3-3506-4055, Fax: +81-3-3506-4150). (Source: *JETRO*, February 1992)

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Twenty per cent efficiency single crystalline silicon solar cells

Sharp Corp. has developed a 5 x 5 cm single crystalline silicon solar cell with a conversion efficiency of 20.4 per cent. Based on a 5 cm square substrate, this new cell brings solar energy a step closer to realistic cost performance.

Generally, the longer wavelengths of incident sunlight penetrate deeper into the solar cell, reaching the rear-face electrode. To effectively use the energy of sunlight at these wavelengths, it is necessary to use metals with a high rate of reflection for the rear electrodes. Conventionally, aluminium has been used. Using silver, an element with excellent solar reflective characteristics, more efficient use of sunlight at longer wavelengths is attained. This boosted conversion efficiency by 0.2 per cent, up to 19.5 per cent.

A solar cell effective surface area can be increased simply by making the surface electrodes smaller, thus blocking less light. However, decreasing the size of these electrodes increases the internal electrical resistance, and the overall efficiency remains about the same. In the past, the shape of the electrodes was determined by the relationship between this resistance and the conversion efficiency. Using computer simulation of the electric current generated at each point in the electrodes, the company precisely ascertained the electrical resistance at all points, and the influence of specific electrode shapes on the solar cell. Based on this, the optimum shape for the surface electrodes was determined, and this provided a 0.9 per cent increase in conversion efficiency up to 20.4 per cent.

Solar-generated power is the ideal replacement for fossil-fuel power generation. The main drawback is the relatively poor economic performance of solar cells. The cost per watt output has not yet approached the levels provided by conventional sources. Companies are now committing substantial research and development resources in an effort to decrease costs by increasing efficiency.

The advanced new single crystalline solar cell is related to the polycrystalline solar cell Sharp was commissioned to develop by the New Energy and Industrial Technology Development Organization (NEDO) as a link in the Sunshine Project of the Ministry of International Trade and Industry (MITI) Technology Center. (Sharp Corporation, Corporate Public Relations Div., 8, Hachiman-cho, Shinjuku-ku, Tokyo 160. Tel.: +81-3-3260-8362, Fax: +81-3-3260-1822). (Source: *JETRO*, February 1992)

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Photovoltaic modules for solar vehicle use minimizing output loss

Sharp Corp. has developed a family of high-efficiency, thin-profile photovoltaic modules for use in solar automobiles. These modules include a bypass diode installed on a one-for-one basis with each solar cell.

Conventional photovoltaic (PV) modules experience a severe drop in output when the surface of the solar cells is partially shaded or if the cell is partially cracked (crazing). In some cases, the modules stop working altogether. For modules connected in series, a partially shaded or cracked cell affects the entire module, causing a precipitous drop in output, even though only a single cell is covered or defective.

For example, in a PV module consisting of 36 individual cells connected in series, when one cell is completely shaded, output drops to less than 20 per cent of normal (Sharp calculations) with no bypass diode, in contrast to a drop of approximately 85 per cent (Sharp calculations) of normal when a bypass diode is installed with the cell. The new photovoltaic modules connecting a bypass diode in parallel with each PV cell minimizes this type of power output drop and allows the module to function normally with maximum output.

In addition, these modules use square cells with a 17.1 per cent conversion efficiency achieved through the use of a surface stabilizing film and fine-line electrodes, leading to highly efficient, thin and lightweight cells. As a result, module conversion efficiency reaches an impressive 16.0 per cent.

In designing and fabricating these devices, Sharp aimed at providing the optimum photovoltaic module ensemble for use in solar vehicles by boosting power output and reducing the weight of the building-block PV cells. The difficulties of mounting on curved surfaces received careful consideration, and, as a result, a flexible structure was adopted. This family of PV modules represents a rich and varied set of 12 different modules meeting race rules and regulations. (Sharp Corporation, Corporate Public Relations Div., 8, Hachiman-cho, Ichigaya, Shinjuku-ku, Tokyo 162. Tel.: +81-3-3260-8362, Fax: +81-3-3260-1822). (Source: *JETRO*, January 1992)

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Development of 22.5 per cent efficient GaAs PV cell

The Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, has developed single-sun photovoltaic cells with an efficiency of 22.3 per cent, the highest in Europe.

The institute used gallium arsenide to reach the record level. The world's record for GaAs cells is 25.7 per cent, achieved by the United States Solar Energy Research Institute, Golden, Colorado, using metalorganic chemical vapour deposition.

The German researchers say they produced their GaAs solar cells with the simpler liquid-phase epitaxial method. (Excerpted from *Int'l Solar Energy Intelligence Report*, 3 May 1991)

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New test capabilities for photovoltaic modules

SERI (Solar Energy Research Institute, 1617 Cole Blvd., Golden, Colorado 80401-3393, USA) has long been setting standards of excellence in testing photovoltaic (PV) modules under both artificial and natural sunlight. Now engineers in the PV Measurements and Performance Branch have greatly enhanced SERI capabilities by installing two new simulators.

One new simulator is a computer-controlled environmental chamber and light source that can test the largest PV modules manufactured today. The chamber is unique to the PV industry. It allows modules to be tested to all currently used standards.

With a volume of about 300 square feet, the chamber can simultaneously expose ten 4-foot by 8-foot modules to selected thermal and humidity conditions. The chamber can cycle modules at temperatures of -94° F to 248° F and as much as 85 per cent humidity.

Modules can be cycled individually while being exposed to an argon light that represents terrestrial sunlight. The filtered argon arc source simulates 0.1 to 2.3 sun intensities.

The second instrument now being installed is a Spire 240A simulator for testing panels with open-circuit voltages of as much as 100 volts. This simulator can test thin-film modules as well as crystalline cell modules over a range of 0.3 to 1.3 suns. (Source: *SERI S&T in Review*, Spring 1990)

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Solar electric training and awareness workshop

Experts from 12 African countries, the Federal Republic of Germany, the USA and Sri Lanka met in Nairobi in 1991 to share their experience in the dissemination of photovoltaic technology in the countries of Eastern and Southern Africa. At the Regional Solar Electric Training and Awareness Workshop, organized by the Kenyan organization KENGO, it became clear that the dissemination of photovoltaic technology has, to date, had few chances in this part of Africa. Reasons given for this were the high costs and the need to import the photovoltaic panels and other components.

Now, however, the experts reported, a dynamic commercial market for photovoltaic technology has emerged in the African countries represented, alongside the dominant State market. This development is particularly marked in Kenya, Zimbabwe and Botswana. Some 10,000 photovoltaic lighting systems have been sold and installed commercially in Kenya since 1986.

In Zimbabwe the company SOLARCOM assembles photovoltaic panels from imported cells. In this way the amount of hard currency needed to import the photovoltaic components has been cut. The Ministry of Energy then accorded photovoltaic technology higher priority in rural electrification schemes. The founding of an "Industrial Association of Solar Energy" is being discussed. In Botswana the Botswana Technology Centre, BTC, offers testing facilities for charge regulators and other photovoltaic components.

The experts discussed primarily the technical and economic aspects of the dissemination of photovoltaic technology. In the practical part of the two-week workshop demonstrations were held on how to install photovoltaic lighting systems. (Source: *GATE*, February 1992)

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Solar-powered airport

The first solar-powered airport in the United States began operations in spring of 1992 in a remote area of south-east Utah, far from the existing electric power grid. Solar Engineering Services, the Lacey, Washington-based company that designed and installed the power system at Cal Black Memorial Airport in San Juan County, sees it as part of a rapidly expanding market for solar-powered facilities in remote regions of the western United States. (Extracted from *International Solar Energy Intelligence Report*, 18 May 1992)

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A report on 3rd AIT-WHO Training Course on Solar Refrigeration Repair and Maintenance

Solar Photovoltaic (PV) powered refrigeration systems have been increasingly used for storing vaccines in rural dispensaries lacking electricity from the grids. Other similar applications are widely accepted for the improvement of living standards of people in remote and non-electrified areas. Simple to operate and environment friendly, the solar PV powered systems require low operating and maintenance costs. To achieve widespread and satisfactory dissemination the major obstacles to be overcome are not only the high initial cost but also the necessity to have sufficient technicians fully trained in sizing, installation, maintenance and repair of such systems, especially in the developing countries.

To successfully tackle these obstacles, the third in a series of training courses on Solar Refrigeration Repair and Maintenance was organized by the Asian Institute of Technology (AIT) with support from the World Health Organization (WHO). Held from 3 to 14 February 1992, the course trained 15 participants from 12 different nations. The course consisted of lectures, discussions, demonstrations and hands-on exercises and the facilities of the Energy Park of the Energy Technology (ET) Division of AIT were utilized. The first two training courses had already trained 42 participants from more than 20 countries of Asia and the Pacific.

The facility for PV powered refrigeration in the Energy Park consists of four different solar refrigerators, measuring instruments, tool kits and a set of training materials and can accommodate about 20 participants at a time. With such an arrangement, the training course laid special emphasis on hands-on exercises in order to prepare suitably trained personnel capable of fully managing the solar PV powered refrigerators.

A course evaluation was conducted through questionnaires completed by the participants. Well appreciated by all the participants, the training procedure was rated excellent by most of them. The training period was felt to be too short and difficulties were encountered in comprehending the topic on solar motion. The organizers have thoroughly assessed the trainers' and trainees' performance and necessary changes will be made for the 4th training course scheduled for 17-28 May 1993.

More details regarding the training course are available in "Report on 3rd AIT-WHO Training Course on Solar Refrigeration Repair and Maintenance", 3-14 February 1992, Energy Technology Division, Asian Institute of Technology, Bangkok, 1992, 31 p. (Please note under "Past Events and Future Meetings", on page 78, announcement on the "4th AIT-WHO Training Course on Solar Refrigeration Repair and Maintenance, 17-28 May 1993.) (Source: *RERIC* NEWS, September 1992)

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Four-terminal stacked solar cell with 20.3 per cent conversion efficiency

Two professors of the Faculty of Engineering Science, Osaka University have succeeded in achieving a new record conversion efficiency of 20.3 per cent with a tandem solar cell of 4 mm square.

This tandem solar cell is a P-N heterojunction type with amorphous silicon as an interface buffer layer, silicon carbide as a wide gap heterojunction window and polycrystalline silicon as a back ohmic contact layer. The new cell with four terminals has high photoconductive properties with efficient absorption of light of different wavelengths and introducing a large amount of photons to the bottom cell.

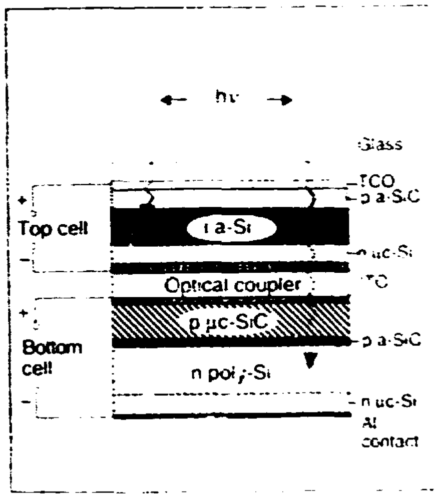
The stacked cell high conversion efficiency was achieved by fabricating the amorphous silicon top cell by a plasma enhanced chemical vapour deposition (CVD) process at a low temperature.

Sharp Corp. developed a 5 cm square mono-crystalline silicon cell with a conversion efficiency of 20.4 per cent last year. However, the monocrystalline silicon involves a difficult manufacturing process requiring a high energy level of 1,500° C, making the process costly.

Amorphous silicon can be produced by a simple process and at low cost, but the conversion efficiency is as low as 11 per cent, it also deteriorates with surface ageing and has a relatively poor spectral response in a long wavelength region of the solar radiation spectrum.

The new cell produced by the plasma CVD technique at about 250° C has a high conversion efficiency. The bottom cell has a vapour deposited crystalline silicon under polycrystalline substrate, and aluminium is deposited as the electrode. On polycrystalline substrate amorphous silicon carbide and crystalline silicon carbide are laminated, and tin indium oxide is vapour deposited as the electrode.

For the top solar cell, the glass substrate has vapour deposited transparent electrically conductive film, amorphous silicon carbide, silicon, crystalline silicon and tin indium oxide. The thickness of the amorphous silicon top cell is designed to be as thin as possible to permit a larger portion of solar radiation to transmit into the bottom cell, while retaining performance. The reduction of amorphous silicon thickness resulted in degradation in the amorphous silicon cell, largely improving the reliability of the cell. (Osaka University, Faculty of Engineering Science, 1-1 Machikaneyama-machi, Toyonaka City, Osaka 560. Tel.: +81-6-844-1151, Fax: +81-6-853-1362.



Structure of four-terminal stacked solar cell

(Source: *JETRO*, July 1992)

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The Massachusetts Photovoltaic Center

The Massachusetts Photovoltaic Center, located at Logan International Airport in Boston, USA, has been established to promote the development of photovoltaic technology and to assist the Massachusetts photovoltaic industry in exporting their products to developing countries.

To achieve this goal, the Massachusetts Photovoltaic Center provides four main services: the Demonstration Center, the Export Assistance Service, the Technology Program, and the Financial Component.

The Demonstration Center provides both displays and hands-on exhibits illustrating the fundamentals of this technology and featuring round-the-world applications. Fact sheets and specific information packages are distributed at the PV Center. The PV Center's staff is equipped to work with visitors and can schedule tours of the Massachusetts Photovoltaic Industry.

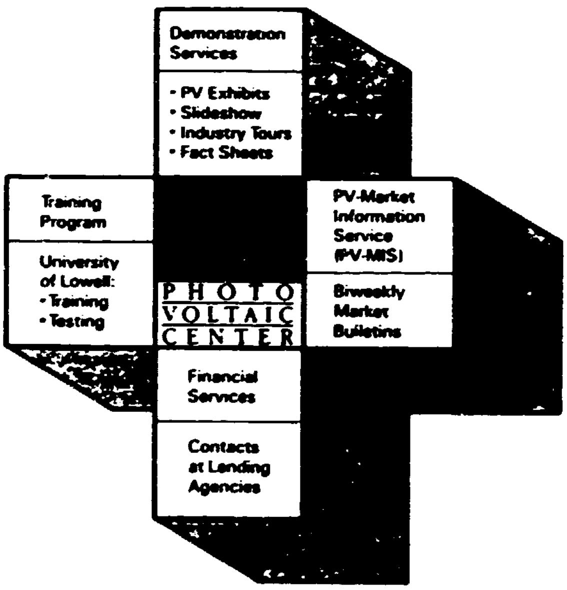
The Export Assistance Service consists of the Market Information Service (PV-MIS). The PV-MIS provides businesses and universities with bi-weekly reports of overseas PV marketing leads. These bulletins provide complete coverage of all PV-related tender and project announcements.

The Technology Program is a combination of training and evaluation services provided by the University of Lowell. Training courses, which began in the spring of 1987, are designed and tailored to address the needs of a variety of international audiences including government officials, energy policy and procurement personnel system designers, equipment installers, operators, and maintenance personnel. Operational research and demonstration systems will include water pumping, refrigeration, grain drying, and village electrification.

The Financial Component offers Massachusetts Photovoltaic Companies access to federal business export services. In addition, a Resource Library at the PV Center includes 500 periodicals, books, reports and articles on photovoltaics, finance and business.

In conjunction with these specific services, the PV Center offers meeting and workshop facilities, and is a one-stop information resource for purchasing and consumer material about photovoltaics.

MASSACHUSETTS PHOTOVOLTAIC CENTER



For information about the Massachusetts Photovoltaic Center and its services and programs, write:

The Massachusetts Photovoltaic Center
One Massachusetts Technology Center Suite 300
Harborside Road
Logan International Airport
East Boston, MA 02128 U.S.A.

Telephone: 617-567-2864
Telex: 510-601-3742

For specific information about training programs and course schedules at the University of Lowell, write:

Photovoltaic Program
University of Lowell
Olney Hall OG5
One University Avenue
Lowell, MA 01854 U.S.A.

Telephone: 617-453-0020

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Centre for Photovoltaic Research

At Portici, near Naples, Italy, ENEA is managing a centre for photovoltaic research. This facility includes a building of 60,000 cm covering an area of 12,500 sq. m with a staff of 150 researchers and technicians. The activities of the centre are presently focused in three technology branches: (1) photovoltaic cells based on amorphous silicon and its alloys, (2) photovoltaic cells based on polycrystalline composite semiconductors, and (3) photovoltaic cells based on high-efficiency gallium arsenide. In the first case, the centre is producing modules of amorphous silicon with a 5 per cent efficiency output with a future output of 10 per cent. The ultimate goal is at least 15 per cent. Concerning photovoltaic cells based on polycrystalline thin films of indium and copper diselenide and cadmium ditelluride, a 14 per cent efficiency rate has been obtained at low cost and at considerable time duration.

Beginning with these results, scientists are studying the possibility of selecting a sedimenting technique especially suited for industrial production. For the third case concerning thin film cells based on composite polycrystalline semiconductors, they are studying various aspects of the sedimenting of transparent and conductor oxides with the method of spray pyrolysis obtaining a conversion efficiency of over 30 per cent.

Photovoltaic powerplant

The Italian National Agency for Electricity (ENEL) has announced the construction of a 3-MW photovoltaic powerplant in the Naples region. The new powerplant, expected to cost 42 billion lire (about $35 million), will satisfy the energy needs of a community of 7,500 inhabitants. The project will be carried out jointly with Pacific Gas and Electric with relative exchange of information, results, and projects for the diffusion of solar plants. The powerplant will employ modules made of polycrystalline silicon manufactured by Italian companies such as Ansaldo, Italsolar, and Helios, but will also compare features and efficiency with modules acquired from Photowatt (France), Solarek (United States) and Kyocera (Japan). (Source: *European Science Notes Information Bulletin*, April 1991).

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The Energy Conservation Centre of Thailand (ECCT): A profile

The Energy Conservation Centre of Thailand (ECCT) was set up in 1987 as a private, non-profit, implementing agency to provide energy management services to industrial and commercial sectors as well as carry out public campaigns for energy conservation. ECCT, started under the co-supervision of the National Energy Administration (NEA) and the Federation of Thai Industries (FTI), received financial support from the national government and technical support from various national and international institutions like the Asian Institute of Technology (AIT), French National Agency for Energy Management (AFME), German Agency for Technical Cooperation (GTZ), Swedish Agency for International Technical and Economic Cooperation (BITS), United Nations Development Programme (UNDP), etc.

The following are the objectives of the Centre:

(i) Respond to the national energy conservation policy;

(ii) Disseminate, promote and provide technical information and advisory services related to energy management and energy conservation to both public and private sectors;

(iii) Create public awareness in energy conservation;

(iv) Serve as a technical information centre for new energy technology;

(v) Coordinate the public and private sectors concerned in energy conservation activities.

In line with its objectives, the Centre has focused on activities like:

- Engineering and consultancy services;
- Technical information and advisory services;
- Training and seminars;
- Public campaigns and promotion.

The Centre has so far completed a number of projects and case studies, carried out training programmes and seminars to foster energy management or conservation matters.

Detailed information can be obtained from:

The Energy Conservation Centre of Thailand
c/o National Energy Administration
17 Rama I Road
Pathumwan, Bangkok 10330
Thailand.

(Source: *RERIC NEWS*, September 1992)

Texas Solar Center

A solar energy centre opened in Texas in June 1992. The developers hope that this will make the state of Texas the solar energy trade centre of the world.

Dedicated specifically to the development and commercialization of solar energy products, the Texas Solar Energy Center (TSEC) will function as an integrated manufacturing, sales, distribution and demonstration complex open to any company selling solar-powered or solar-related products. (Kevin Conlin, Texas Solar Energy Center, 13130 Stafford Road, Stafford, Texas 77477, USA) (Extracted from *International Solar Energy Intelligence Report*, 18 May 1992)

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Some useful contact organizations

Africa

Centre Regionale d'Energie Solaire (CRES), BP 1872, Bamako, Mali. Fax: +223 224538

African Research Centre for Solar Energy (ARCSE), Bujumbura, Burundi.

Centre de Développement des Energies Renouvelables, Rue El Machaar El Haram, Issil, B.P. 509, Marrakesh, Morocco. Fax: (04) 30.97.95

Australia

International Solar Energy Society (ISES), PO Box 124, Caulfield East, 3145 Victoria, Australia

Murdoch University Energy Research Institute (MUERI), Murdoch, WA 6150. Fax: (09) 310 6094

Victorian Solar Energy Council, 10th Floor, 270 Flinders Street, Melbourne 3000, Australia. Tel.: (03) 654-4533

Solar Energy Research Institute Western Australia, 13 Howard Street, Perth, Australia. Tel.: 326-4240

India

Tata Energy Research Institute (TERI), 7 Jorbagh, New Delhi 110003. Fax: +9 111 462 1770.

Jordan

Renewable Energy Research Centre, Royal Scientific Society, P.O. Box 925819, Amman, Jordan. Fax: (962-6) 844-806

SE Asia

Asian Institute of Technology (AIT), PO Box 2754, Bangkok 10501, Thailand. Fax: +66 2 5290374

Europe

Renewable Energy Enquiries Bureau, ETSU, Harweli, Oxon OX11 0RA, UK. Tel: +44 0235 432450

FAKT, Association for Appropriate Technology, Gansheidstr. 43, D-7000 Stuttgart 1, Germany. Fax: +49 711 600608.

GTZ-GATE, PO Box 5180, D-6236 Eschborn 1, Germany. Fax: +49 6196 79 1115

IT Power Ltd., The Warren, Eversley, Hants. RG27 0PR, UK. Fax: +44 0734 730820

OVE, Danish Organization for Renewable Energy, Int. Secretariat, Willemoesgade 14, DK-2100 Copenhagen 0. Fax: +45 31429095

Projekt-consult, Limburger Str. 28, D-6240 Konigstein, Germany. Fax: +49 6174 22985

Projekt-Planung-Lauterjung, Dipl. ing. Helmut Lauterjung, Grauhofstrasse 16, D-3340 Wolfenbuttel, Germany. Fax: +49 5331 46760

Institut für Solarenergieforschung - ISFH, Sokelanstrasse 5, D-3000 Hanover 1, Germany

SKAT, Tigerbergstrasse 2, CH-9000 St. Gallen, Switzerland. Fax: +41 71 22 46 56.

Stockholm Environment Institute, Box 2142, 103-14 Stockholm, Sweden. Fax: +46 8 723 0348. Independent member of Mini Hydro Power Group (MHPG)

(Source: *Appropriate Technology*, Vol. 18, No. 3, December 1991)

3. APPLICATIONS

What's new under the sun

In the late 1960s and early 1970s, solar energy was largely perceived as a factor on the economic fringe, touted by Utopians and counter-culture spokesmen as the answer to the pollution and cost problems of oil or nuclear energy, but regarded by industry and agriculture alike as essentially "experimental".

No more. Solar energy is now firmly established among mainstream power sources, increasingly competitive with its fossil and solid fuel rivals, and steadily developing new applications as unit costs decrease. Along with a growing acceptance of solar options as realistic, has come the sophistication on the part of its proponents to know where it is not realistic - including applications in developing countries where local conditions may make other energy forms more practical.

But the potential of solar power remains enormous: all of the electricity produced in Latin America and the Caribbean in 1989, some 585,398 kilowatt hours (kWh), could be obtained - if solar energy reached an optimum - with an average solar radiation of 7 kWh per day per square metre and a conversion system operating at an average efficiency of 12 per cent (a conservative estimate) on an area equal to a square with sides only 44 km long.

Already, solar units of various sizes are employed for domestic, commercial and industrial heating, home and farm outbuilding heating and cooling, drying of agricultural and fish products, water desalination and potabilization, salt and mineral concentration, greenhouse production of vegetables and flowers, irrigation and pumping systems, domestic and street lighting, rural television, sterilization of water, rural radio and telephone systems, telemetry equipment, road and railway signals, relay stations, airport signals, refrigeration of vaccines and medicines, navigation buoys and offshore platforms, cathodic protection, portable power supplies for camping and travel, and low-voltage electronic equipment - to name but a few uses.

A tour of the sector reveals the current and likely future state of the solar arts, and what technologies are now available:

Two broad groups

The wide variety of technologies used to exploit solar energy can be divided broadly into those that use thermal and those that use photovoltaic processes to convert solar radiation into useful power. Thermal systems can be active or passive, while photovoltaic systems may be either stationary or "tracking", namely, capable of turning to follow the path of the sun across the sky.

Passive thermal systems - Heating and cooling of homes is a prime application for passive solar energy systems, which aim to eliminate the need for fossil fuels by harnessing, storing, distributing and discharging solar energy for heating, or rejecting, extracting or excluding it for cooling.

Here, meteorological and terrain factors must be integrated into the architectural design of buildings, at the same time that material, design and construction errors are avoided. Buildings and building lots must be oriented respecting the annual sunshine (insolation) and dominant wind patterns - for example, absorbing as much solar radiation as possible for heating applications while sheltering the interior from cold winds (large south-facing windows, windowless north-facing walls, or construction of homes against hillsides that block prevailing winds, are typical features). Mechanisms (such as fixed overhangs) that control heat gain from solar radiation must be correctly oriented, to either minimize or maximize heat gain. The shape, orientation and slope of roofs, the location and use of balconies, receding elements and skylights, and the size, location and shape of windows must also maximize (for heating) or minimize (for cooling) solar radiation effects. Natural ventilation and lighting must be designed to take advantage of the same factors.

The thermal insulation properties of materials to be used in floors, walls and roofs must be taken into account according to climate, while colours and textures must be capable of reflecting or absorbing solar radiation in accord with the overall plan. Living areas, kitchens and bathrooms should be located to benefit from the most favourable orientation.

Passive systems have been largely perfected over the past decade and constitute the most widely adapted solar technology. Particularly in countries with high concentrations of urban inhabitants, they are cost-effective and make rational use of renewable energy.

Active thermal systems - Active systems have moving parts, such as motors or pumps, and can use either stationary or tracking collectors. Stationary systems harness energy via fixed collectors, which convert solar radiation into heat and transfer it to a working fluid (water, oil, or some gases of high molecular weight), in effect acting as heat exchangers. There are three types of stationary collector:

(a) *Flat-plate collectors*, consisting of a flat metal absorber surface, blackened for better absorption and welded to a network of tubes. This is housed in a box with thermal insulating material on the down side and one or several panes of glass covering the side facing the sun (fibreglass and transparent plastic sheets have also been used, but deteriorate quickly). The collector is installed at whatever angle maximizes its efficiency at the geographical latitude of the site.

Such collectors have an efficiency of 40 per cent in low-temperature applications (30°-40° C.)

Now mass-produced, they can be purchased at an annual average cost of US\$ 100/m^2, compared to US\$ 230/m^2 in 1980, expressed in 1990 dollars.

(b) *Evacuated tube collectors* are similar to flat-plate collectors, except that they operate in a vacuum or at very low pressure between the absorber and its surrounding glass tube. This reduces or eliminates energy loss due to conduction or convection.

Units are set up on a support structure, at the optimum angle for the site's latitude. They need no insulating material on the side away from the sun. This type of collector is produced commercially, with an efficiency of roughly 25 per cent. Current costs are about US\$ 250/m^2, compared to US\$ 450/m^2 in 1980, in 1990 dollars.

(c) *Solar pond collectors* in their simplest form are no more than a mass of water with a vertical salt gradient, the salt concentration increasing with depth to the bottom of the pond. Most of the solar radiation on the pond surface is absorbed by the water and the bottom of the pond. As this energy is absorbed, the deeper layers of water get warmer and their density decreases. Without a mechanism to stop it, such as the salt gradient, a convection current would be produced, moving from the bottom to the top of the pond. As the hot layers moved to the top, heat would be lost through convection, evaporation and radiation to the atmosphere. However, by maintaining stratification with the salt gradient, transfer of heat from the lower to the upper layers is achieved only through conduction. This process is sufficiently slow for the deeper layers to maintain a relatively high temperature (often around 100° C).

Heat extraction from the pond bottom by heat exchangers is a delicate procedure, and the extraction rate must not destroy or modify the salt gradient. Part of the success of solar ponds is due to the parallel development of low-temperature turbines that operate with fluids of high molecular weight, such as freon, making it possible to generate mechanical and electrical energy efficiently at a temperature of around 100° C. Controlling the stratification and maintaining the required salt gradient are the major technological problems encountered. Pond systems are presently being perfected and operate at an average overall efficiency of 10 per cent, including both conversion and storage of energy.

When temperatures above 300° C are required, the low energetic density of solar radiation makes it necessary to use collectors that concentrate radiation and can follow the daily movement of the sun in one or two directions.

Tracking active thermal collectors include scattered systems, which use linear or focal concentrators, and those with a solar receiving tower, using flat mirrors or heliostats to concentrate solar radiation in certain high points above them.

In scattered systems, each mirror module or collector has its own absorber, while in solar receiving towers all the mirrors are focused on a single, common absorber. Solar concentration systems only use direct solar radiation.

Scattered systems, such as those using parabolic trough collectors, have reached commercial stage and can now harness 74 per cent of the available energy, at a cost of US\$ 215/m^2, compared to US\$ 500 in 1980, expressed in 1990 dollars. With these systems, electricity can be generated with an efficiency of 26 per cent at a cost of US\$ 0.15 per kilowatt hour, compared to US\$ 3 to US\$ 4 per kWh in 1980. Solar receiving tower mirrors are now being developed with an efficiency of 60 per cent, at a cost of US\$ 100/m^2, compared to US\$ 300/m^2 in 1980.

Photovoltaic systems - The solar cell - a semiconductor that converts solar energy directly into electricity - is the basic component of photovoltaic systems, and produces a current of 10 to 40 mA per cm^2, at 0.5 to one volt. These cells are wired in series or parallel, to produce an electrical output of two to 60 peak watts (watts generated by the radiation of 1,000 W/m^2, at a temperature of 20° C). A photovoltaic generator is formed by an array of such modules, in sufficient number to produce the desired amount of electricity. Depending on the difference between solar radiation patterns and electricity load, storage systems and auxiliary systems will have to be used, as well as the required electromechanical or electronic elements, so the equipment can function efficiently for the preselected duration of its operation.

The complexity of a photovoltaic system depends on the electric load characteristics. It can be as simple as a solar cell connected directly to a pocket calculator, as its power source. Or it can be far more complicated, forming part of an electricity network in which its use is optimized by combining it with other generating units, such as oil-fired or coal-fired generators.

Three basic steps are involved in generating electricity in a photocell. Electron holes in excess are generated by the absorption of photons. The carriers must be separated by an internal electric field produced by joining two semiconductor materials. The carriers must then be collected into the outgoing electricity flow.

Solar cell research is being developed basically around five materials: silicon (single crystal, polycrystalline and amorphous), gallium arsenide, copper/indium/selenium, cadmium teluride, and indium phosphide.

With single crystal and polycrystalline silicon cells, an efficiency of 20.6 per cent has been obtained. With amorphous silicon, which requires less material and energy for its production, an efficiency of 14 per cent has been reached. Gallium arsenide achieves a record efficiency of 31 per cent, with a low concentration cell of 350 to 500 suns. Copper/indium/selenium ($CuInSe_2$) cells have been tried recently with satisfactory results, reaching an efficiency of 13 per cent. Important progress has been made with cadmium teluride (CdTe) cells, obtaining an efficiency of 11 per cent. Finally, indium phosphide (InP) cells have obtained an efficiency of 19 per cent.

The first photovoltaic modules were manufactured in 1958, and by 1970 they were being used to generate electricity in space satellites, although this cost US$ 155 per peak watt. In 1980, the cost was down to US$ 20 per peak watt. At today's cost of US$ 4 per peak watt, they are mass produced and have penetrated the commercial market with efficiencies of 12 per cent for stationary system modules and 25 per cent for solar concentration and tracking systems. The cost of electricity thus generated is now US$ 0.25 to US$ 0.35 per kWh, compared to US$ 1.5 to US$ 3 per kWh in 1980. The useful life of modules has increased to 20 years, and certain companies offer a 12-year guarantee.

In terms of state of development, efficiency and constantly decreasing cost, the evolution of solar energy systems is moving inexorably toward a promising future, and a substantial role in meeting world energy demands. (Further information: International Solar Energy Society, c/o Ballinafad Research, P.O. Box 97, Ballinafad, Ontario, NOB 1HO Canada) (Source: *CERES 133, FAO*, January-February 1992, article written by Manuel Martinez, researcher with the Laboratorio de Energía Solar, at the Universidad Nacional Autónoma de México)

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Developing photovoltaic technology in China

China is a vast country of 9.6 million km^2, and 80 per cent of its 1.1 billion people live in rural areas. Conventional electricity is difficult to produce or transport to isolated places like the prairies, mountains and islands. The potential for solar energy applications is huge, and Xin Mingyi explains how the versatility of photovoltaic equipment makes it an ideal method of producing power.

China began to study photovoltaic (PV) technology in 1958, and Chinese PV cells were first used in a satellite in 1971. In 1973 the terrestrial applications of PV were investigated, the first application being a navigation aid in Tanjing harbour. In recent years the output of PV cells has increased significantly and their cost has decreased. In 1989 the production capacity of the PV products manufactured in China reached 4.5 MW. With ten Chinese manufacturers (see table 1), 22 universities and 16 research institutions involved in research and development, great progress has been made. The China National PV technology Development Centre (CPVC) is a PV R&D centre which brings together many of these institutions to work on PV under the leadership of the State Science and Technology Commission and the Ministry of Energy.

New developments

PV production technology in China has improved a lot in the last 10 years. The efficiency of the cell has increased and the production cost has been reduced. The production process has been developed further, and silk-screen printing technology has replaced the old method. The reliability and quality of the product has improved, and many of the materials used in production, like high polymer film and silver paste, can now be manufactured in China.

The experiments in PV application in China show that in some locations and conditions PV is very competitive with conventional energy. Analysis has shown that when the ratio between consumption and distance from grid to user is smaller than 100 W/km, a PV power supply is more economical than conventional electricity. The main applications are:

Navigation aids: PV has proved itself a brighter, more reliable, labour-saving and maintenance-free source of power for navigation aids in lakes, rivers and seas. The payback period for this application is two to three years. Of the 438 lighthouses and beacons in South China, 107 are equipped with PB power supplies.

Communications: Small communications equipment, wireless telephones, and micro-wave communication relay stations are all suitable applications for PV. The microwave relays in Yulongyang, Shanxi Province and Shangyu, Zhejiang Province are all equipped with PW power supplies and the results are good. PV is now in place in more than 20 stations, and 27 more have been scheduled to be installed.

Railway signals: China has more than 5,000 railway stations, of which 1,500 are without conventional or stable electricity supplies. In 1978 the Ministry of Railways began to use PV as the power supply for the railway signals and now 14 of its branches are using 150 PV-powered signals.

Table 1

PV manufacturers in China

Name	Location	Technology	Production capacity	Date of start-up
Ningbo (solar power electric factory)	Ningbo Zhejiang	Monocrystal silicon	300kW	1976
Kaifong (solar cell factory)	Kaifong Henan	Monocrystal silicon	300kW	1975
Yunnan (semi-conductor factory)	Kunming Yunnan	Monocrystal silicon	500kW	1980
Chronar Corp. (solar electricity	Harbin Heilongjiang	Amorphous	1,000kW	1988
Daming Ltd. (solar power company)	Shenzhen Guangdong	Crystalline silicon	1,000kW	1988
Baotou (solar devices factory)	Baotou Neimonggu	Monocrystal silicon	50kW	1982
Solar Ltd. (electricity company)	Nanjing Jiangsu	Monocrystal silicon	300kW	1985
Changjiang (power plant)	Wuhan Hubei	Crystalline silicon	50kW	1968
18th Research Institute	Tianjing	Monocrystal silicon	20kW	1978
Huamei Photovoltaic Ltd.	Qinhuangdao Hebei	Monocrystal silicon	1MW	1989

Broadcasting and television: A typical application of this type is the television transmitter station in Dachen Islands, Zhejiang Province, which is part of the China-EC Decentralized Energy System. It is maintenance-free and powered with a 2 kW PV generator. Before the installation of this station the local people could receive only one programme and the reception was poor because of the remoteness. Now residents have four channels with very clear images, and the number of television sets has jumped from only a few to more than 1,000.

Agriculture, forestry and animal husbandry: The main users in this field are black light lamps, lights for rubber collecting, forest fire probes, electrical sprayers, electrical animal fences, and pumps. The PV pumps developed by Xian Jioatong University and Zhejiang University are now under trial.

Households: Remote settlements on islands, in the mountains, and in the prairies cannot be connected to the grid economically but can use PV generators.

PV power stations: Some regions, such as Tibet, Xinjiang, and Inner Mongolia, again cannot be connected to the grid, but have plenty of sun. These PV power stations are a very competitive alternative power supply. China has two PV stations with a capacity of 2 kW each, and a third one is under construction in the Ali area of the Tibet autonomous region.

Hydrology, meteorology and earthquake monitoring: Many provinces have already started to use PV as the power supply for remote meteorology, hydrology and earthquake-monitoring stations. Compared with other alternatives PV is cheap and reliable.

Other applications include solar boats and cars, cathodic protection for pipes and sluices, solar clocks, lights and battery chargers, and a variety of toys.

Targets

In an effort to make PV systems still more reliable and affordable, clear targets have been set to guide PV technology development in the future.

To make full use of existing facilities and speed up technical improvement, thereby increasing the cell's efficiency and production capacity. Special efforts are being made to fill the gaps in mass producing the fundamental materials for PV cells, like wafers and silver paste.

To emphasize the research in large-scale crystal ingot and high-speed wafer-thin slicing. Attention will also be paid to the manufacture of high-efficiency cells with large surface areas, reducing material consumption and rejection rate.

To focus efforts on improving the efficiency and reliability of amorphous silicon, to increase the conversion efficiency and control the degradation of amorphous silicon cells.

To research and develop compound semi-conductor cells and to develop new types of PV cells.

To emphasize the importance of systems-research, including components development.

To disseminate PV technology continuously and make plans to organize demonstration projects. Four regions, Tibet, Inner Mongolia, Xinjiang and Qinghai and some islands and mountain areas have been chosen to demonstrate the PV power stations and other hybrid systems.

To establish a PV product-testing centre to control the quality and standardization of PV products.

To install a silicon material production line using the country's abundant silicon resources to ease the shortage of raw materials.

The PV market in China is very large. There are 35 countries, 200 islands, and 196 million people without electricity, and many specialist applications. The CPVC thinks the potential market for PV products in China in the next five years is at least 10 MW. The Chinese Government is supporting PV with favourable tax policies and financial support for research. If the development of new PV applications continues at its present rate, the living conditions of millions of Chinese people will improve remarkably.

(Xin Mingyi is at the China National Photovoltaic Technology Development Centre, Zhejiang Provincial Energy Research Institute, 91 Huanchengxilu, Hangzhou 310007, China) (Source: *Appropriate Technology*, Vol. 18, No. 3, December 1991)

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Renewable energy applications in Mongolia

The Mongolia People's Republic occupies an area of 1,565,000 km^2 with a population of 2 million people. Around 129,000 Mongolian families in rural areas rely on animal husbandry for their living, 81,000 of these families are essentially nomadic.

The Mongolian Government is keen to stem the flow of the population to the towns by improving living conditions in rural areas. The Government has declared its intention to provide electricity to all rural families over the next few years. Renewable energy is playing a leading role in this initiative.

A typical family in a yurt (round tent) needs energy for lighting (5 hours per day), television (4 hours per day) and radio (15 hours per day), amounting to a daily energy requirement of only 150-200 Wh. A single solar photovoltaic module of 40-60 W is sufficient to meet this.

Several hundred photovoltaic systems have now been installed in Mongolian households. The Research and Production Corporation for Renewable Energy (part of the Ministry for Energy, Mining and Minerals), based in the capital Ulan Bator, has been assembling and distributing these systems, which originate from Europe, the USA and China, and evaluating their performance.

The Institute of Physics and Technology, meanwhile, has pursued a photovoltaic research programme. Photovoltaic cells on monocrystalline silicon wafers have been produced and then assembled into modules in Ulan Bator. The United Nations Development Programme (UNDP) has supported this activity and, following a market assessment undertaken by IT Power, a pilot production plant has been proposed.

Solar energy is also used for water heating. About 2,000 m^2 of solar collectors supply water to rest houses, hotels and children's "pioneer camps" which are mostly occupied in the summer months. The Research and Production Corporation has also developed large volume solar water heaters specifically for the warming of drinking water (from snow or ice) for livestock, to help these animals survive the harsh Mongolian winters. (Extracted from: *RERIC NEWS*, Vol. 14, No. 3, September 1991)

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Solar banana drier

In response to a request from the CTCS Network at the Caribbean Development Bank, Oliver Headley and his research team from the University of the West Indies, St. Augustine, Trinidad and Tobago, have recently designed and constructed a solar banana drier at San Ignacio in Belize. This drier has a 102 sq. ft. solar collector covered with 0.5 mm thick clear PVC plastic sheet connected to a drying chamber containing six trays. Air circulation is aided by a chimney rising 8 ft. above the top of the drying chamber which itself stands on 4 ft. legs to give the collector a slope of 16.6 degrees. The total height of the chimney is 15 ft.

This drier is designed to dry ripe bananas at a rate of 200 lbs per day and the materials and construction methods were specifically chosen to allow it to be built in rural areas with readily available skills such as carpentry and sheet metal working. Five modules of this size have now been built in Belize and more should be built in Jamaica in the near future. The drier is a modified version of the rock bed drier, an 84 sq.ft. example of which has been used to dry spices in Grenada since 1983. Since the wooden frame is not strong enough to carry several hundred pounds of rocks, it is proposed to use a wood stove as a back-up heat source for cloudy days, rainy periods or extra production at night. Only clean hot air would be passed into the drier, the flue gases from the burning wood being discarded through a separate chimney. (Source: *RERIC NEWS*, Vol. 14, No. 3, September 1991)

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Solar-powered school

Baan Sai Kao School, in the Tha Sae district of Chumphon Province, has become well known for its solar power unit.

The school is located in a remote setting only 12 kilometres from the border with Burma. It provides six years of primary education for a total of 350 children. When Typhoon Gay struck Chumphon two years ago, Baan Sai Kao was badly damaged.

After the storm, the school received help from the Government to construct a new, more permanent building. Along with it came a gift from Argonshu, a Japanese monastery, of a solar power generator which supplies electricity for all lighting and audio-visual equipment.

The solar system was designed and manufactured by BP Thai Solar. The system comprises of solar panels, batteries, an electronic control unit and a panel-holding structure.

The solar array at Baan Sai Kao consists of 68 modules, each measuring roughly a metre by half a metre, weighing about 7.5 kilogrammes, and delivering 58 watts of power. This system is capable of generating an average of 20 kilowatts of power a day. It has 36 batteries with a total storage capacity of roughly 60 KW.

The cost-effectiveness of solar-generated electricity depends on functions and places of use. A study comparing a diesel generator to solar power conducted by the Electricity Generating Authority of Thailand concluded that in places where demand for electricity is not high, the cost of that produced by solar power is less than that produced by diesel generator.

An advantage of solar power is its flexibility for future expansion. At Baan Sai Kao School, there are already plans to extend the system. Another array of 14 panels will be installed to provide villagers with a battery-charging facility.

Almost every villager today owns a 15-volt battery to provide electricity for one tiny light bulb at night. Some have a television set. The school's headmaster estimates that about 200 families in the area use batteries and have to recharge them every 7-10 days.

Each battery charge can cost as much as 100 baht (= US$ 4.00): 15 baht for the charging itself, 60 baht for transport to town and back, and the rest for lunch in town plus loss of a day's work.

The villagers will save a lot of time and money if they can charge their batteries directly from the expanded solar power unit. (Source: *RERIC NEWS*, Vol. 14, No. 3, September 1991)

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Solar water heating

Cyprus has a 30-year history of solar power use and about 1 million square metres of solar collectors are installed throughout the country. According to the Director of the Higher Technical Institute in Nicosia, 90 per cent of the island's houses and 50 per cent of its hotels use solar power for water heating. The systems are manufactured locally and are also exported. Solar power currently displaces 175 million kWh of electricity a year (4.5 per cent of the island's annual primary energy use).

The Higher Technical Institute is currently testing a solar prototype to power hospital X-ray equipment on behalf of the World Health Organization (WHO). WHO is interested in reliable alternative power systems for hospitals in the developing world. The prototype has been used at the Nicosia General Hospital since 1989 without resort to other electrical back-up. The institute is also working on a solar-powered water treatment system to recycle domestic "grey" water which is discharged from showers, wash basins and washing machines. (Source: *RERIC NEWS*, Vol. 14, No. 3, September 1991)

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Solar water desalination plants

The Pakistan Council of Scientific and Industrial Research (PCSIR) conducts various research and development projects in the fields of: applied chemistry; plastic and polymer; pharmaceutical and fine chemicals; food science; biosciences; minerals and metallurgy; glass and ceramics; pilot plant and engineering; standard calibration and instrumentation; solar energy; leather technology; fuel science and technology; precision engineering; rural technology; and environmental studies and conducts research related to solar water desalination as follows:

(i) Vajuto Desalination Plant

A solar water desalination plant (capacity 250 gpd) was fabricated and installed at Village Vajuto (Taluka Mithi, Distt. Tharparkar). The pumping of brackish water is being performed at present by an electric pump using an electric generator; this will be replaced by a photovoltaic-powered submersible pump.

Another plant of the same capacity will be installed soon in Mithi Taluka at a place indicated by the SAZDA (Sind Arid Zone Development Authority).

(ii) Pakistan Navy Water Desalination Plant, Gwadar

A 6,000 gpd solar water desalination plant based on sea-water is being fabricated for the Pakistan Navy at its establishment at Gwadar; the work is being undertaken under a contract agreement to supply the plant on turn-key basis at a cost of Rs. 7.661 million.

(iii) Manbai-J-Tar Desalination Plant

The 250 gpd solar still installed in Taluka Chachro in 1988-1989 under the instruction of the Prime Minister is being maintained and operated by the SERC. The desalination complex is based on 250 ft. deep-well brackish water pumped by an electric submersible pump and by another pump run on power from a windmill.

(iv) Islamkot Desalination Plant

The WAPDA (Hyderabad Division) has given its letter of intent for getting a 250 gpd plant installed at Islamkot Grid station. Final details are being worked out. (Scientific Information Centre, Pakistan Council of Scientific and Industrial Research, 39 Garden Road, Saddar, Karachi 74400, Pakistan) (Source: *RERIC NEWS*, Vol. 14, No. 3, September 1991)

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The (solar) power to communicate

Solar-powered distance education programmes have proven valuable and effective in rural areas where it is particularly difficult to attract and retain high-quality teachers. In one area in Mexico, high school classes are broadcast through solar power over a 6-hour period. The estimated cost? Approximately US$ 2,200-2,400 per school. In health, solar-powered two-way radios have been installed as part of the communications system for remote medical systems in Mexico, Ecuador, Kenya, Zimbabwe and Guyana. In each case the radios operate efficiently over distances of more than 200 km. In the Gambia, solar-powered VHF radio communication systems are being used between health centres in remote areas and the capital city for consultations and emergency medical assistance.

Developing countries the world over are discovering a reliable and low-cost source of energy for small-scale communications systems: the sun. In the Sudan, where messages were previously carried by hand for long distances or by poorly transmitted telex or radio, the United Nations Development Programme (UNDP) has designed a solar-powered packet radio system for communicating data from five field offices scattered throughout the country. UNDP's success has led to plans for similar systems in the Philippines, Jamaica, Ethiopia, Mozambique, Tanzania and Lesotho.

Energy in rural areas has been commonly provided through gasoline-powered generators. In recent years, however, solar energy or photovoltaic systems (PV) have been successfully used in a variety of applications including electrification, water supply and as the examples show, communications. PV systems permit closer contact between rural and urban centres without the incessant noise and complicated maintenance of a generator.

Over 10,000 PV systems are being installed world wide every year. These range from relatively large telecommunications systems operated by Governments or private companies to small radio systems used in homes or in local communication. Whether the application is fibre optic cable systems for data transmission or mobile telephone, PV systems are cost-effective and reliable. (Extracted from *Development Communication Report*, No. 75, April 1991)

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Solar power for communications

Whilst solar electric power is used in a diversity of applications sometimes it is best to focus on just one, to see the types of application that can benefit from this technology. One such is the railway industry.

Both railway communications and signalling require power supply systems and in many countries laying in mains cable is either a very expensive or impractical option.

Optical fibre systems offer an ideal application for solar power given their inherent low power consumption. As part of a programme installed for Indian Railways by NKT, they are using 97 solar power systems to power some of the multiplex equipment down the line.

As well as fibre optics, radio systems are similarly ideal for solar use. In a project for Aydin Monitor for Ghana Railways, solar power was again chosen due to lack of an existing reliable mains supply at many of the locations. BP Solar supplied 43 systems along this line powering radios.

Other systems have or are in the process of being supplied by BP Solar systems for use by railway authorities in Bangladesh, Sudan, Thailand, Mozambique, Nigeria, Australia and Zambia.

As railway communications and signalling systems become more sophisticated and widespread, there will be a need for equally sophisticated cost-effective and reliable power systems. In those countries without extensive grid systems but abundant sunlight, solar power is providing ideal power solution. Reportedly, as with many other solar applications, railway authorities using solar will soon outnumber those not. (Source: *Tech-Monitor*, September-October 1991)

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Africa's sunlight aids the deaf

The sun will soon be helping deaf people in developing countries to hear. The Botswana Technology Centre has developed a tough, low-cost hearing aid which uses solar power to recharge its battery.

Conventional hearing aids are not really appropriate in developing countries. They die very quickly because ordinary batteries leak, or else they do not get used because people in remote places cannot get batteries.

The hearing aid consists of a standard earpiece attached by a cable to a clip-on box measuring 5 cm by 7.5 cm by 2 cm and weighing 60 grams. This contains the electronics plus a tiny nickel-cadmium battery that was designed originally for use in radio pagers. A solar panel is built into the casing. Exposing the panel to five hours of direct sunlight will recharge the battery fully and give between 50 and 80 hours of use, depending on volume.

For maximum toughness, the casing is injection-moulded in polycarbonate, a material which is also used for motorcycle crash helmets. The casing was designed to withstand being dropped from a height of 1 metre on to a concrete floor. None of the parts of the hearing aid are replaceable: it is simply intended to last about five years.

After encouraging results from field trials, the hearing aid will go into production early in 1993. It will be assembled locally at Camphill, a workshop for disabled people which recently received 7,800 pulas (about £2,300) for tools from the British High Commission. (Source: *New Scientist*, 19/26 December 1992)

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Three-year performance and reliability analysis of a 4 kW amorphous-silicon photovoltaic system

Abstract

A 4 kW photovoltaic (PV) power system composed of 144 Sovonics R100 amorphous-silicon alloy modules was constructed in south-eastern Michigan, USA in early 1987. During more than five years of continuous operation, the system and its components have been reliable and durable. Analysis of array performance has shown initial degradation, followed by stabilization. Cyclic efficiency variations have been found to be related to solar spectrum, ambient temperature and past history of temperature.

Introduction

This project was initiated as a joint venture between three electric utilities, a PV manufacturing company, two research-oriented organizations and an educational institution specializing in alternative energy technologies. The Consortium, led by the Detroit Edison Company (2000 Second Avenue, Detroit, MI 48226, USA) also consists of Consumers Power (Jackson, MI), the Board of Water and Light (Lansing, MI), Energy Conversion Devices/Sovonics Solar Systems (Troy, MI), Oakland Community College (Auburn Hills, MI), Michigan Energy Resource and Research Association (Detroit, MI) and the Electric Power Research Institute (Palo Alto, CA).

The project was developed as a learning tool for the utilities involved and as a public demonstration of the capabilities and realities of PV energy production. Towards those ends, the participants have profited greatly from the experience and knowledge gained.

Amorphous PV materials are uniquely different in their operating characteristics from crystalline and polycrystalline cells. They are sensitive to a different part of the solar spectrum, they exhibit strong seasonal efficiency variations and are annealed by the long summer heat soak. Another significant difference is that amorphous silicon is subject to an initial efficiency degradation (the Steabler-Wronski effect).

The 4 kW amorphous-silicon PV facility studied in this project was constructed at the Auburn Hills Campus of Oakland Community College north of Detroit, Michigan. It was first energized on 6 May 1987 and has been in continuous operation since that time. During the 40 months since system start-up, considerable data have been collected and analysed. Conclusions have been reached with regard to efficiency variations caused by temperature, solar spectrum, material degradation and annealing.

Conclusions

The 4 kW amorphous-silicon alloy PV demonstration facility installed and operated by the Detroit Edison Consortium at Oakland Community College near Detroit, Michigan has proven to be durable and reliable within the solar regime of south-eastern Michigan. It has performed largely as expected and has continued to deliver electrical energy to the campus on a daily basis.

Array efficiency varies monthly according to a seasonal pattern. Winter efficiency declines as ambient temperature drops. Summer efficiency improves, but on a delayed basis after a long period of warm summer temperatures which anneal the amorphous material. Instantaneous variations in efficiency are seen to be the result of changing solar spectrum, calculated as air mass. The initial Steabler-Wronski effect degradation, which resulted in a permanent efficiency reduction, occurred over an initial 17-month period, after which the array stabilized around an annual average efficiency of 3.56 per cent. (Exerpted from *Solar Cells*, 30 (1991))

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Early experiences of the 15 kW NMPC demand-side management photovoltaic project

Abstract

The Niagara Mohawk Power Corporation (Niagara Mohawk Power Corporation, 300 Erie Boulevard West, Syracuse, NY 13202, USA) has begun operation of a photovoltaic (PV) system in upstate New York, USA to study the summer peak load reduction capability of grid-connected PV systems serving commercial buildings. The roof-retrofitted system consists of a 151 m^2 polycrystalline silicon module area rated at 15.4 kW d.c., three one-axis trackers, and a high efficiency power-conditioning unit. Preliminary results from the first two months of operation indicate PV system output is at a high fraction of capacity when the building experiences its electrical demand peaks. Ongoing studies are evaluating a cross-section of commercial customer load profiles in terms of the probability of peak demand reduction. (Excerpt from *Solar Cells*, 30 (1991))

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Development in rechargeable battery

A power storage system developed by researchers at New South Wales University, Australia may improve the utilization of solar power. Their instantly rechargeable vanadium redox battery is poised for its first trials in a vehicle. The redox cell does not wear out but retains its charge indefinitely and can be recharged simply by replacing the electrolyte.

The battery exhibits a much higher energy efficiency and stores energy at a cheaper cost than the other available batteries. Developed by the University's School of Chemical Engineering and Industrial Chemistry, the battery uses vanadium pentoxide, a chemical with which Australia is richly endowed. The battery is expected to open the way for the use of solar, wind and the other renewable energy sources in remote communities. (Source: *RERIC NEWS*, September 1992)

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Tapping soil water through solar energy

As disclosed from a report by scientists Anil K. Rajvanshi and Narendra J. Zende of the Nimbkar Agricultural Research Institute (NARI) Phaltan, Maharashtra, India, NARI scientists are using solar energy to tap inaccessible water in soils and feed it to tree seedlings in the arid regions of the state.

Their method essentially involves digging a pit in the ground and covering it with a solar water evaporation still which traps the sun's heat. The heat makes the soil water evaporate and condense to liquid form which is collected and later fed to seedlings surrounding the pit. The stills are reusable.

Studies at NARI not only revealed 100 per cent survival rate of such seedlings but also a better growth rate than the rainfed seedlings. In semi-arid and arid regions the roots of seedlings are too shallow to pull up the tightly bound soil water for use.

In their experiments, the NARI scientists dug 0.9 by 0.9 by 0.6 cubic metres pits which produced, on an average, 300 ml of water every day. The survival of seedlings with low water supply hints at the possibility of using a drip irrigation system. Experiments are being carried out on plants such as *Leucaenia leucophala* and bamboo, two species with relative susceptibility to water stress. (Source: *RERIC NEWS*, September 1992)

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Solar cell for outer space

Sharp Corp. has developed a back surface reflector (BSR) type solar cell for outer space with a high conversion efficiency of 13.8 per cent in outer space, and they have been selected for use in two new

International Telecommunications Satellite Organization's satellites, INTELSAT-VII A No. 6 and No. 7.

Solar cells for outer space must have high resistance to deterioration of output when exposed to intense radiation such as the protons and electrons produced by the earth's magnetic field in outer space, and to the extreme temperature differences between exposure to the sun and in the earth's shadow. INTELSAT VII A satellite cells must withstand thermal fluctuations of 305° C between the maximum temperature of 125° C and minimum temperature of -180° C.

The primary power cells designated for supplying power to these satellites can supply power with the excellent output characteristics demanded for the increased output of INTELSAT VII A satellites by the development of a fine grid pattern technology based on the photolithography method and the optimization of the PN junction formation. The cell also has a high resistance to intense radiation and thermal shock in outer space. It can withstand thermal shock for 10.9 years, the life-cycle of the INTELSAT VII A satellites.

The solar cell chip is a three-layered chip, the upper part made of ordinary amorphous silicon has an amorphous silicon carbonate cell absorbing short wavelength light, and the lower part has an amorphous silicon-germanium cell highly sensitive to long wavelength light. The initial conversion efficiency was a maximum of 12 per cent, with an initial yearly deterioration factor of 5 per cent.

The quality of the amorphous compound layer was improved and technology for adjusting the film thickness to generate the maximum electric current developed. The conversion efficiency was improved and the deterioration factor lowered. The manufacturing method is based on chemical vapour deposition, and the cost is not so high compared with conventional methods.

The company is improving the reliability of amorphous solar cells in the project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) as a link of the national large-scale R&D project, or the Sunshine Project. (Sharp Corporation, Corporate Public Relations Div., 8 Ichigaya Hachiman-cho, Shinjukuku, Tokyo 162, Japan. Tel: +81-3-3260-8362, Fax: +81-3-3260-1822)(Source: *JETRO*, April 1992)

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4. MARKETING

Solar energy: more attractive

Costs for both photovoltaic (PV) and solar thermal processes have fallen sharply in the past 20 years. Solar electricity is already competitive with "conventional power" for many specialized applications. The evidence indicates that costs will continue to drop, making solar power plants an even more attractive alternative to fossil-fueled and nuclear plants.

PV cells are semiconductor devices that transform light energy into direct-current electricity. When two semiconductors dominated by opposite electrical charges are in contact, free charge leaks across the common boundary and becomes fixed as ions in the region adjacent to the boundary. At the interface, the fixed (but opposite) ions create an electric field that sends free electrons one way and free holes the other.

In the dark, no current flows in the PV cell. But when it is illuminated, electrons are freed from their bound states in the valence band and move into the conduction band. The free charges can then be separated by the electric field. Since the electrons and holes are separated in opposite directions, a current will flow as long as the cell is illuminated and electrically connected to an external load.

The 1978 Solar Photovoltaic Energy Research, Development & Demonstration Act established a goal of "production of electricity from photovoltaic systems cost-competitive with utility-generated electricity from conventional sources". Japan, Germany and other foreign countries also have PV research programmes.

SERI points out that PV costs have continued to plummet, to $20 per watt by 1977 and $4 to $5 per watt by 1988. Even at those "low" prices, a PV module large enough to power just one 40-watt light bulb still costs up to $200. So, SERI observes, "further cost reductions are essential".

The process of designing PV technology boils down to selecting appropriate semiconductors to produce a strong, homogeneous built-in electric field; making sure the semiconductors can absorb as much sunlight as possible; designing the cell so that the sunlight can be absorbed very close to or in the electric field region; and fabricating the device so that its electric properties favour good performance. Current PV R&D projects are dealing with all those facets - and also always keeping costs in mind.

Crystalline silicon PV cells, quite similar to those pioneered by Bell Labs in the 1950s, still dominate the market. So a brief examination of just what is involved in making them will serve as a useful point of departure for looking at alternative PV technologies, some already on the market but most still in the laboratory.

First, the silicon for PV cells must be ultrarefined, to the point that there is less than one non-silicon atom per billion. Then it is melted and slowly drawn from a crucible to form a large single crystal. A diamond saw slices the crystal into thin wafers - wasting about half the crystal in the process. Dopants, for example boron and phosphorous, are added to form the electric field. Metal contacts are placed on the front and back of the PV cell to carry the current. Groups of such cells are mounted on a plate and wired together to form a PV module. The silicon surface is protected with plastic or glass. Typically, a module is a square metre or less in size, with a generating capacity of 50 to 150 watts. And typically, commercial crystalline silicon PV modules are about 11 to 14 per cent efficient, although module efficiencies of 16 per cent have been achieved in the laboratory.

SERI notes that more than 100 industry and academic research teams have worked to upgrade and automate the manufacture of crystalline PV cells. Efforts continue to reduce even further the cost of purified silicon, to develop high-speed crystal-pulling and wafer-slicing techniques, and to improve the overall design and efficiency of modules, with 17 per cent efficiency seen as a reasonable goal for commercial modules. Siemens Solar Industries (formerly Arco Solar) is the largest US producer. Major foreign producers include Siemens in Germany, Sharp and NEC in Japan, and BP Solar in the UK.

Polycrystalline PV cells can be made by casting sheets of molten silicon. The cost of manufacture is lower than for crystalline silicon because the casting process is inexpensive. Efficiencies are lower, because the grain boundaries between the crystals hinder the PV process. Proponents predict, however, that polycrystalline PV modules will achieve commercial efficiencies of 14 per cent or better, at competitive prices. Major producers of cast polycrystalline cells include Solarex in the US, Kyocera in Japan, and Wacker in Germany.

Texas Instruments (TI) takes an altogether different approach to the problem with its "Spheral Solar" silicon PV cells. Metallurgical-grade silicon is melted to form tiny spheres. In the process, impurities "sweat" to the surface and are removed by mechanical or chemical means. Then p- and n-materials are diffused into the spheres. At the end of this process, the interiors are p-doped and the exteriors n-doped (or vice versa, depending on the need).

Some 17,000 of the doped spheres are imbedded in and bonded to an aluminium foil grid about 4 inches square. That grid holds the spheres in place and also forms one of the electrical contacts. The spheres are then etched on the other side, exposing their reverse-doped interiors. Another aluminium foil is bonded to the newly exposed surfaces, forming the second electrical contact for the cells. What one has then is 17,000 tiny silicon PV cells, all wired in parallel, with an output comparable to that of conventional silicon cells of similar size.

No vacuum sputtering, lasers, or other high-cost processes are needed to make the cells. Because the cells are flexible, manufacturing yields approach 100 per cent for module lamination. The cells provide the advantages of thin-film modules with the stability of crystalline silicon. TI and Southern California Edison have embarked on a joint research programme to commercialize the devices.

Much current PV research aims at developing semiconductor materials that can be deposited as thin films on glass or metal substrates, rather than cut from ingots or cast in sheets. Whereas crystalline silicon cells are on the order of 100 to 300 μm thick, the thin-film semiconductors may be as thin as 0.5 μm. Even if the thin-film material is more expensive on a weight basis than crystalline silicon, much less is required. Also, fabrication tends to be simpler and more amenable to automation. Thus, overall costs may be lower.

A number of thin-film semiconductors are under development, including amorphous silicon, copper indium diselenide, cadmium telluride, and gallium arsenide. However, the only thin-film PV material currently in large-scale commercial production is hydrogenated amorphous silicon (α-Si:H) and its alloys. As the name suggests, this material is also silicon-based, but unlike crystalline silicon, it is glasslike, with no lattice structure. Amorphous silicon is not inherently photovoltaic, but becomes so when grown with small amounts of hydrogen or fluorine.

In principle the amorphous silicon PV cell resembles its crystalline counterpart, but there are differences in the details of construction. To make a typical single-junction device, a layer of a transparent conducting oxide (TCO) is deposited on glass to provide one of the electrical connections for the cell. Then a p-doped layer of amorphous silicon, and "intrinsic" (undoped) layer, and an n-doped layer (referred to collectively as p-i-n) are successively deposited. Finally, a back contact layer, which can be of metal or TCO, is deposited.

There are variations on the theme. For example, alloys such as α-SiC:H or α-SiGe:H can be used to achieve higher PV conversion efficiency. Efficiencies on the order of 10 to 12 per cent are now obtained more or less routinely with single-junction p-i-n cells. But it is generally accepted that modules must be at least about 15 per cent efficient to be useful for central power generation applications in the US. And it will be difficult to achieve further dramatic increases in efficiency with single-junction cells.

However, one of the advantages of thin-film PV cells is that they can be stacked in series in a multijunction configuration. With this approach, different materials are used for the respective layers. Low-energy photons are directed to cells made of narrow band-gap materials and high-energy photons to cells made of wide band-gap materials. The materials are placed in order of descending band gap, so that the widest band-gap material faces the incident light. The result of all this is that a larger portion of the solar spectrum is converted to electricity, and efficiency goes up. According to calculations, it should be possible to achieve efficiencies of about 24 per cent, using a combination of materials with 2.0-, 1.7- and 1.4-eV band gaps. In theory, even higher efficiencies, 35 to 40 per cent, should be obtainable with multijunction devices.

A continuing problem with amorphous silicon PV devices has been that they undergo some sort of photodegradation, with accompanying loss of efficiency, upon initial exposure to light. The effect levels off with time, and can be compensated for in designing systems. Improvements in engineering design and materials have reduced the severity of the problem. Despite a lot of research, however, the reasons for the light-induced degradation still are not clearly understood, and the search for answers continues.

Among the polycrystalline thin-film PV candidates, copper indium selenide/cadmium sulphide cells are perhaps currently in the lead. One of the $CuInSe_2$/CdS cell's advantages is its inherent long-term stability. It seems to be immune to the photodegradation that occurs with amorphous silicon PV devices.

Since Boeing scientists first fabricated a 10 per cent efficient cell in 1981, $CuInSe_2$/CdS R&D has accelerated. Current efforts are focusing on, among other things, the development of simpler, non-vacuum film deposition processes, higher efficiency and, of course, lower costs.

Meanwhile, three laboratories (University of South Florida, Ametek and Photon Energy) have reported cadmium telluride PV devices with efficiencies between 10.5 and 12.5 per cent. A major advantage for the CdTe cells is that they can be made by low-cost processes. There have been difficulties in making stable electrical connections to CdTe cells, but according to SERI, innovative designs are overcoming the problem.

Crystalline semiconductors based on group III-V elements offer perhaps the best hopes for dramatic improvements in PV cell performance. Efficiencies better than 20 per cent have been achieved with cells made with various combinations of gallium, indium, arsenic and phosphorous. Scientists at Sandia National Laboratories have obtained peak efficiencies higher than 30 per cent with their "mechanically stacked multiple junction" devices combining gallium arsenide and silicon cells.

Replacing solar cells (the expensive parts) with optical elements made of inexpensive plastic or glass will lower total costs. In fact, the solar cells do work more efficiently in concentrated light, which also helps lower the cost.

But there are offsetting factors. The concentrator must aim directly at the Sun, so a tracker is needed. Perhaps a greater disadvantage is that the concentrator only works in direct sunlight, not in cloudy weather. Nor can the concentrator focus the diffuse blue skylight that makes up about 20 per cent of usable solar energy. In contrast, flat-plate solar cells can generate significant power even under cloudy skies, and they can use the diffuse skylight's energy.

PV technology, in general, is not yet competitive with bulk power generated by conventional means. However, PV is already quite competitive in many remote, low-power applications where the actual amount and cost of the energy is less important than reliable, low-maintenance operation. More than 20 utilities now use PV for a variety of low-power installations.

A national cooperative research demonstration project, Photovoltaics for Utility Scale Applications (PVUSA) was started in 1986 to assess the potential of solar energy for commercial power generation.

Phase I of the PVUSA programme, now nearing completion, has involved installing and testing nine different kinds of "emerging module technologies" (EMT). These use many of the advanced PV approaches described earlier, including multijunction cells and concentrators. Each technology is provided by a different manufacturer.

Each EMT system consists of a 20-kW array of a manufacturer's modules, along with an inverter that converts the direct current generated by the PV modules to three-phase alternating current, and a support structure designed and installed by PVUSA. A data acquisition system monitors the systems' performance, the weather, and fluctuations in the sun's energy. Most of the systems have been installed at a Davis, California, site; others are in Hawaii, New York, Texas and Virginia.

Phase I also includes a "utility scalable" portion to test three complete vendor-supplied PV systems, two nominally sized at 200 kW and one at 400 kW. Testing of these larger systems will give utilities realistic information about reliability, performance, and operation and maintenance costs, along with hands-on experience with PV systems connected to an electric utility grid.

Pacific (PG&E) has been among the leaders in promoting utility use of "alternative" energy sources. Planning is now under way for Phase II, which will include pilot tests of more EMT and utility scalable systems, to be installed between 1992 and 1995.

Although PV conversion of sunlight energy to electricity seems to be getting more R&D attention these days, one cannot ignore the potential of solar thermal processes. In fact, there is about 360 MW of solar thermal capacity now on line in California, generating power for sale to utility companies there.

A solar thermal power plant is a lot like an ordinary steam turbine power plant, except that it gets its heat from the sun rather than from fossil fuels or nuclear reactors. In most current solar thermal plants, reflective concentrators focus the sun's radiation on tubes containing a synthetic oil heat transfer fluid, heating it to more than 700° F - hot enough to convert water to super-heated steam in a conventional heat exchanger system.

Typically, the concentrators have been the costly part of solar thermal installations. But just as with PV, costs have come down steadily - by a factor of eight between 1978 and 1990 - and new designs should cut the cost by another two thirds.

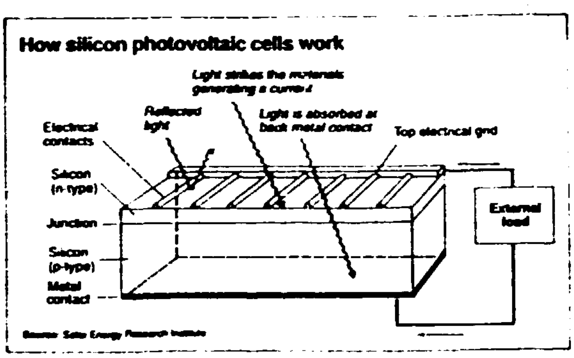
For example, researchers at Sandia and at Solar Kinetics, a Dallas firm, have developed a new concentrator, the stretched-membrane parabolic dish. Instead of the heavy glass mirrors traditionally used, the dish has a very thin metal membrane. A pressure- and vacuum-forming operation is used to give the membrane its curved shape. Then the membrane is covered with a shiny polymer film to form the reflective surface.

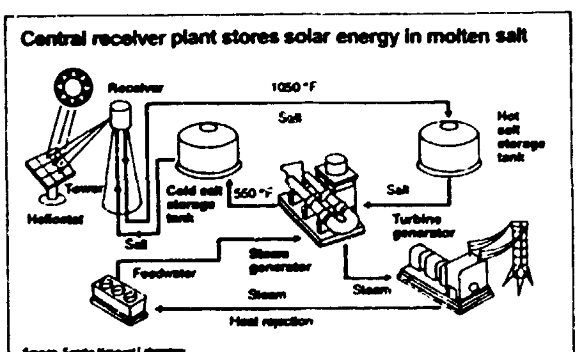
Not only does the thin membrane cost less than glass, it also weighs a lot less. As a result, supports do not need to be so massive, allowing further cost reductions. In early performance tests, the concentrator has surpassed expectations, achieving a peak concentration of 5,400 suns and generating peak power of 21.2 kW at its focal point. The same technique can also be used to make the flat mirrors needed for heliostat fields.

Meanwhile, Sandia is touting its central receiver power plant technology as "ready to be commercialized". Central receiver plants consist of a field of heliostats - sun-tracking mirrors - that concentrate the light onto a receiver that absorbs the energy and transfers it to a heat-transfer medium. Earlier plants have generated steam directly, or have used a heat-transfer oil. With either method, it is not practical to store energy for use when the sun is not shining.

The new approach uses a molten nitrate salt. The salt is heated and used to make steam, just as with earlier systems. However, some of the molten salt can be stored and used as needed, even at night. The cooled salt recirculates to the receiver for reheating when the sun is out again. Sandia points out that the molten salt can be stored at atmospheric pressure, so the storage system can be relatively simple.

Work also continues on a distributed-receiver approach employing a reflux pool boiler. In this method, a pool of molten sodium is used to transfer heat. The sodium boils, then condenses as it transfers its heat to the heater tubes of a Stirling engine. Then it drips back into the pool to be heated again. Energy from the Stirling engine can be used to generate electricity. Sandia notes that the engine has high thermal-to-electric conversion efficiencies.





(Extracted from *C & EN*, 17 June 1991)

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Mexico funds renewable energy; US starts technical assistance

Since 1989 Mexico has installed nearly 10,000 solar photovoltaic systems for lighting, water pumping, refrigeration, and other educational, health-care and social service needs in isolated villages. Most of the projects have been small, single-panel systems.

The Mexican programme - Programa Nacional de Solidaridad - includes such photovoltaic applications as ice-making for preserving fish for market in coastal villages, and improved agricultural production and processing operations.

Mexico has little choice but to expand its renewable energy programme, since rural areas are making greater demands for energy and it is inefficient to connect them to main grids. Photovoltaic energy will remain the single, largest contributor to the rural energy programme. (Excerpts from *International solar energy intelligence report*, 29 November 1991)

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ISAAC solar icemakers: field trial report

A recently developed larger version of the Isaac solar icemaker is now undergoing field trials in a remote fishing village in Mexico. The new "Double Isaac", developed by Energy Concepts Co. of Annapolis, Maryland produces 150 pounds of ice per day. Using a thermal absorption cycle, the icemaker requires no electricity or moving parts, and consists primarily of pipes and valves, thereby ensuring reliability and low cost.

Maruata, a fishing village on the Pacific coast of Michoacan, is located 60 km from the electric grid and over 100 km from the nearest source of bulk ice for refrigeration. It is home to about 50 fishermen and their families who catch red snapper in nets and dive for langouste and octopus. Due to their remote location, they need to maintain an adequate stock of ice for fish storage, which again is dependent upon the quantity of fish catch.

The Mexican engineering firm CIEDAC, working under sponsorship of the Mexican Government PRONASOL programme, is installing alternative energy systems in the "dark" (unelectrified) areas of Mexico such as Maruata. During a visit to Sandia National Laboratories in Albuquerque, NM, CIEDAC encountered the Isaac prototype being tested there. Their calculations showed that Isaac would provide the needed refrigeration at less than half the cost of other alternative energy systems, and a proposal was initiated.

In anticipation of this project, Energy Concepts began developing the new Double Isaac in the summer of 1991. The state of Maryland provided cost-share assistance through the Challenge Grant programme. Also, the National Renewable Energy laboratory provided funding to do a pre-feasibility study of the design and economic factors pertinent to applying this technology in Mexico.

The project was formally initiated in October 1991. Altogether seven Double Isaacs will be required: three to provide block ice for transport cooling, and four which will directly cool the walls of a cold storage room and be mounted on its roof. The first two block ice units were installed in April and are shown in the accompanying figures. The remaining units will be installed this summer.

PRONASOL estimates that there are 1,000 similar fishing villages in the dark areas of Mexico, and as many as 50,000 in the interior. When these numbers are multiplied by the approximately 40 other similar sunbelt countries around the world, the magnitude of the problem becomes apparent. Serving the refrigeration needs of these villages in a traditional manner would require many new power plants and millions of new halocarbon refrigerators, which would further stress an already overburdened planet. Technologies, similar to the one like Isaac, can truly provide help to the poor section of the human race. (Source: *RERIC News*, September 1992)

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Solar energy stations to generate electricity for remote areas will be built, according to the Ministry of Energy and Mines in Guatemala. A simple solar panel connected to a battery costs $600, and can be used to provide light for a few hours each day. The Guatemalan programme will require financial aid from abroad. Electrification can be used for telecommunications, refrigeration, water pumps, etc.

Scott Sklar of the US Solar Industries Association says most sales of US solar power equipment were to Third World nations in 1990. Some 25 per cent of the sales were to Mexico. Sales of solar generating equipment have increased 30 per cent in the past two years. (Source: *New Scientist*, 9 November 1991)

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Powerful photovoltaic concentrator

Ideal for remote and rural electricity needs, the "PowerSource Photovoltaic Concentrator" magnifies solar irradiance by 90 times for 50 per cent more power than a standard PV module using less refined silicon, says the company. Its features include two-stage optical concentration with fresnel and lens and passive sun tracking that uses a Robbins solar tracker. Its modular design has 75-watt tracking modules with a range of 400 watt to 50 kilowatt tracked arrays. Easy to install and maintain, it comes with a 10-year warranty. Price: $600. (Michael F. Kitchen, Owner, Independent Energy Systems, Dept. CN, WA. 98109, Duvall, USA. Tel: 206-788-4569 or 206-548-8251, (Source: *Commercial News USA*, October 1991, No. 8)

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Process lowers solar cell cost

Metal-organic chemical-vapour deposition is being used to turn cadmium telluride into low-cost solar cells at Georgia Tech. University at Atlanta, GA, USA. It is part of development work aimed at eventually reducing the cost of solar energy from $4 to $5 per watt currently to $1 per watt, which is necessary to compete with conventional power sources. (Source: *American Metal Market*, 1 June 1992)

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The following two articles appeared in the *Press Service* of the Federal Economic Chamber of Austria in 1992:

Solarbike

The "Solarbike", a drive system for bicycles powered by solar energy, was developed for longer stretches or gradients. It is operated by a 24-volt electromotor energized by two special batteries with 15 Ah each via a drive roller to the front wheel. Two solar panels and a special charger ensure easy charging of the batteries. It is controlled via a twist-grip gear change that is simple to use. Travelling speeds of up to 30 km per hour with a range of 40 km can be attained. The "Solarbike" is available as an electric vehicle, the batteries being permanently mounted in the bicycle frame, and as a kit for easy installation by the customer. On the occasion of a World Cup race for electric vehicles in Austria, the Austrosolar 90 over Austria's highest mountain, the Großglockner, "Solarbike" has already proven its worth by reaching second place. (Schachner Zweirad-Center, Mittlere Markt 17, A-3361 Aschbach, Austria. Fax: 07448/3681)

Sport-Solar

With the development of Sport-Solar, the Austrian enterprise Solkav-Solartechnik succeeded in marketing the first walkable solar surface. This new product offers the possibility of the multiple use of a surface, above all to the leisure industry. Sport-Solar is suitable as a solar collector for the heating of a swimming pool, as an underground of an artificial ice surface in winter, as a surface for ball game grounds, or as an antiskid pool border and with the aid of a heat pump for heating industrial water or to operate a low-temperature heating system. Sport-Solar, available in the colours black, red, green, and blue, is a surface whose 2.5 cm layer contains the entire technology of a solar collector, an absorber, and a coolant carrier for a saltwater-water heat pump.

(Solkav-Solartechnik, Industriegebiet Nord, A-3150 Wilhelmsburg, Austria. Fax: 027 46/243043)

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A cheaper coating for photovoltaics

A vapour-deposition process developed by Battelle Institute (Frankfurt, Germany) promises to cut the costs of thin-film photovoltaic cells by a factor of five, to $1.30/watt (based on a projected production of 100,000 m^2/year). Called Closed Space Sublimation, the method coats standard window-grade glass with cadmium telluride (CdTe), building films at a rate of greater than 10 micrometers (thickness) per minute. CdTe has a photovoltaic peak-efficiency of 11 per cent, compared with 8 per cent for amorphous silicon.

A flat block of CdTe, heated to 700° C, is held 2-3 mm above the glass surface, which itself is at 500° C. Because of the temperature gradient, the CdTe sublimes across the gap onto the glass. A 1-millibar vacuum and an inert nitrogen purge prevent contamination of the coating.

The next step is to modify the batch process for continuous operation. Battelle is also seeking industrial partners to build a continuous pilot plant. (Source: *Chemical Engineering*, March 1992)

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A boost for solar sales

The Ministry of International Trade and Industry (MITI), Japan is taking steps to boost the installation and use of solar power equipment. Ways to revive research and development efforts in the solar field are now being investigated and under a plan now in preparation, MITI intends to provide incentives or guidelines to municipalities for installation of solar-powered electrical equipments in parks and other public places. Concerned by the high expenses involved in the commercialization of solar power equipment, MITI plans to devise methods to nurture the dissemination of solar-power cells up to the year 2000.

In fact, Japanese solar R&D is progressing in a modest way. At the Shikoku Research Center, an affiliate of Shokoku Electric Power Company, a medium-sized house with solar panels covering most of the roof and featuring batteries for electricity storage was recently unveiled. It even has controllers to transmit electricity to the power grid of the company when the house occupants do not need it. The reduction in external electricity purchases is estimated to be about 30 per cent and by April 1993 the house will come on to the market.

Similarly, a Japanese engineering and energy team is being assisted by the US orbital solar-power programme as a means to promote an environmentally friendly power source in the years to come. Officials from MITI, JETRO, and Mitsubishi Heavy Industries visited a number of US sites including NASA where the research work is continuing. Studies are under way for the transmission of energy from orbiting solar-power stations to ground-based receivers via microwaves. (Source: *RERIC NEWS*, September 1992)

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Programme to reduce costs of photovoltaics

The Department of Energy is providing up to $55 million to US companies for research and development projects to improve manufacturing processes for photovoltaic systems. DOE's photovoltaic manufacturing technology project, one of 11 initiatives in conservation and renewable energy announced last year, is designed to reduce substantially the costs of producing such systems. The first phase of the project, now under way, is helping to pay for companies to identify areas in which R&D is needed to obtain major reductions in production costs. The second phase will develop solutions to problems so identified. Reducing manufacturing costs and getting new technology into the marketplace are two important steps for making US companies more competitive. (Source: *C & EN*, 4 February 1991)

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Sunshine brings water to West Africa

Sunshine is one of the few resources that the Sahel, in West Africa, has in abundance. Water and energy, however, are scarce. Now, five Sahel nations - Gambia, Guinea-Bissau, Mauritania, Senegal and the Cape Verde Islands - have commissioned the German companies Siemens Solar and Bayernwerk to help them use sunlight to electrify and bring water to the region. The project is the largest ever commercially contracted for the building of a solar energy system to date.

The contract is being funded by a consortium of the five states called CILSS, dedicated to combating desertification in the Sahel region and will cost about £10 million. To finance the project, it has solicited funds from the regional cooperation project of the European Community.

According to project plans, 410 solar-powered water pumping stations will be built in the contracting countries and many other facilities will have solar power added. All stations will use modules of standard solar cells made from monocrystalline silicon. These wafers of semiconductor convert sunlight directly into electric current. Each module will generate 50 watts of peak power. A refrigeration unit will require six modules, but a pumping station could need anywhere from 10 to 80 modules.

Although the individual generating units will be small, the project is a big one. When completed, the installations will generate a combined total of 640 kilowatts of electricity. At the end of the estimated four-year construction period, 410 pumping, 89 cooling, 303 lighting, and 33 battery-charging systems will be built. (Source: *New Scientist*, 16 March 1991)

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The sunny side of the street

A Swiss entrepreneur has come up with a new solution to one of the major problems of using solar energy - where to put all the solar cells. Hundreds of acres are needed to generate any significant amount of energy, but meadows and mountainsides would be blighted if they were covered with huge, ugly solar arrays.

Thomas Nordmann of Chur has persuaded the Swiss Government to try installing solar cells alongside an Alpine highway. The cells, mounted for 880 metres atop a sound baffle, provide 100 kilowatts of power to the local electricity grid.

The cells were installed in late 1989 as the first stage in a large-scale experiment in exploiting unused areas for solar energy generation. During the next phase, already under way, Nordmann's firm, TNC Consulting AG, is installing solar cells along a railway line in Ticino in southern Switzerland.

Nordmann will have completed four test sites by 1996, after which the Swiss Government will decide if it wants to continue the project.

Solar cells installed only in the most advantageous areas, says Nordmann, could ultimately provide 11,000 households with up to 45 megawatts of power at peak demand times in winter. If all potential highway sites in Switzerland were used, solar cells could by the year 2000 provide 375 megawatts, as much as a medium-sized conventional power plant.

But the price will have to come down. At present, solar energy from Nordmann's cells costs one Swiss franc (about $0.68) per kilowatt-hour, which is three to ten times higher than the market price of electricity. By 2000, Nordmann hopes that solar energy will be competitive with traditional power sources, at least at the daytime hours when demand is at its peak. The costs would come down through economies of scale and technical improvements, he says. (Source: *Nature*, Vol. 345, 3 May 1992)

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Thin film technology gives cheaper solar power

BP Solar believes it has found a way of drastically reducing the cost of manufacturing solar power-generating panels through the use of cadmium compounds instead of the silicon materials normally employed. The BP method involves creating thin films of two semiconducting materials, cadmium sulphide and cadmium telluride, by simply dipping glass sheets coated with tin oxide into an electro-plating bath containing the cadmium compounds. The films created are just one micron thick.

Silicon films in contract must be created by a more arduous process involving the manufacture of blocks of the material which must then be sliced to the required thickness. The end result is that solar power generated by silicon panels costs around $4.5 per watt. BP estimates, however, that its new technology will reduce that cost by about 75 per cent by the end of the decade. making solar power a genuinely competitive option for electricity generation in appropriate geographical areas. (Source: *Engineering*, February 1991)

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Solar-photovoltaic systems

Utilizing the sun's power for innovative, hi-tec engineering applications, an Israeli company is currently concentrating on the development of a photovoltaic lighting system for remote road junctions. The system produces wide spectrum, anti-glare light, and is road safe.

The products are energy-saving and cost-effective. Based on innovative proprietary, multi-technology designs, these systems are more compact, simple and reliable, with minimal requirement for maintenance. Solar-smart lighting systems are applicable for junctions, security regions, bus stops and road signs; solar-smart mini-refrigerators for storage of food; solar-smart water pumps for third world countries; and solar-smart power supplies for TVs and videos.

Several applications have been successfully marketed in Israel, others are currently being developed. (Source: *Advanced Technologies from Israel*, September - October 1992)

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Monocrystalline silicon solar photovoltaic cell with 22 per cent conversion efficiency

Sharp Corporation has developed a single-crystal silicon solar photovoltaic cell with a conversion efficiency of 22.0 per cent, a 1.6 per cent improvement on cells for mass production.

This newly developed solar cell has two significant improvements in the structure of the back surface. The reflectivity of the back surface is improved using a thin, silicon oxide film between the positive electrode and the silicon substrate to create a structure in which light is reflected from the positive electrode and from the oxide film. Optimizing the conditions under which the back surface is finished, such as thickness of the oxide film and the silicon substrate, and carefully controlling the temperature of heat treatment process following contact formation achieved approximately 90 per cent reflectivity from the back surface (previous reflectivity: 70 per cent) which improved conversion efficiency by 0.4 per cent compared to existing solar cells.

Small holes etched in the oxide film formed the field layer into a dot pattern. This process reduced the surface area of the field layer and suppressed losses of electrons at the positive electrode, achieving an improvement of 1.2 per cent in conversion efficiency.

This high-efficiency solar cell was fabricated in a 2 cm x 2 cm size to make it simple to evaluate the device characteristics. In the future, the company plans to work on larger sizes for full-scale production. (Sharp Corporation, Corporate Public Relations Division, 8, Ichigaya Hachiman-cho, Shinjuku-ku, Tokyo 162, Japan. Tel: +81-3-3260-8362, Fax: +81-3-3260-1822) (Source: *JETRO*, July 1992)

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Low-cost solar cells possible using efficient deposition techniques

Battelle is developing a process for depositing cadmium-telluride films that is surprisingly fast and permits low-cost production of efficient thin-film solar cells on inexpensive substrates, such as window glass.

Technologists have achieved as much as 12 per cent efficiency in the first experimental solar cells, and much higher efficiencies will be possible. In cooperation with industrial manufacturers, Battelle plans to enter the pilot production stage for this very promising type of thin-film solar cell.

Battelle fabricated the first cadmium-telluride thin-film solar cell more than 20 years ago. Since then, technologists have gained a better understanding of the basic processes and material parameters of cadmium-telluride thin-film technology. Battelle's new technique permits top-quality films to be produced at high deposition rates. And, as with photographic films, it should be possible to deposit the cadmium-telluride films on to moving substrates.

Deposition takes place in moderate vacuum and in an inert gas atmosphere, which reduces the cost of producing solar cells. Inexpensive window glass can be used as the substrate material. Battelle's cost estimate for cadmium-telluride cells is roughly 80 per cent lower than the current cost of silicon solar cells.

Interested parties are invited to participate in the venture, which is aimed at producing a large-scale production process. (Source: *Battelle*, No. 71, July 1992)

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5. PUBLICATIONS

The following six abstracts appeared as articles in *Solar Cells*, 30 (1991)

Silicon solar cell materials research: current progress and future needs

Bhushan L. Sopori
Solar Energy Research Institute, 1617 Cole Boulevard, Colden, Colorado 80401, USA.

Abstract

This paper presents a brief review of the research being carried out under the crystalline silicon materials research programme. The primary emphasis of this programme is the development of processes for post-growth quality enhancement of low-cost silicon substrates. The various electronic mechanisms that can be exploited for material quality enhancement are summarized. Major research results of the current programme and some important aspects of future research are identified.

Materials aspects of multijunction solar cells

S. A. Hussien, P. Colter, A. Dip, J. R. Gong, M. U. Erdogan and S. M. Bedair
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911, USA.

Abstract

Atomic layer epitaxy (ALE) was used to grow several components of the cascade solar cell structure in the AlGaAs/GaAs system. An ALE reactor was constructed for multiwafer growth with a growth rate of 0.6 $\mu m\ h^{-1}$. Device quality GaAs and $Al_xGa_{1-x}As$ films were grown with p-type background carbon doping in the ranges 10^{15}-10^{19} cm^{-3} and 10^{16}-10^{20} cm^{-3} respectively. N-type films were achieved by SiH_4 doping, producing carrier concentrations in the range 10^{16}-10^{18} cm^{-3}. In addition, the potential applications of the ALE technique in the photovoltaic field are discussed.

Advances in double-junction amorphous silicon photovoltaic modules

Yukimi Ichikawa and Hiroshi Sakai
Fuji Electric Corp., Research and Development, Ltd., 2-2-1 Nagasaka, Yokosuka, Kanagawa 240-01, Japan.

Abstract

Large-area hydrogenated amorphous silicon solar cells with a two-stacked p-i-n junction tandem structure are practical solar cells with high conversion efficiency and reliability. We attained a total-area efficiency of 10.05 per cent for a 30 cm x 40 cm tandem submodule. We found that the initial degradation of these tandem cells was about 15 per cent of the initial value. Using these results, we discuss the feasibility of a stable 10 per cent efficient a-Si photovoltaic module.

Advances in the development of an AlGaAs/GaAs cascade solar cell using a patterned germanium tunnel interconnect

R. Venkatasubramanian, M. L. Timmons, T. S. Colpitts and J. S. Hills
Research Triangle Institute, Research Triangle Park, NC, USA.

Abstract

In this paper we discuss various aspects of the development of an inverted-grown AlGaAs/GaAs cascade solar cell incorporating a patterned germanium tunnel junction. Topics include the development of the $Al_{0.37}Ga_{0.63}As$ top cell, the growth of the GaAs bottom cell over the patterned germanium tunnel junction, and a technique for selective removal of thin AlGaAs/GaAs heterostructures after lattice-matched growth on germanium substrates. The problems to be overcome for the achievement of around 30 per cent efficiencies in the AlGaAs/GaAs cascade cell under concentrator applications are also discussed.

Review of the application of molecular beam epitaxy for high efficiency solar cell research

Michael R. Melloch
School of Electrical Engineering, Purdue University, West Lafayette, IN 47907, USA.

Abstract

In the last two years, rapid progress has been made in the energy conversion efficiencies of GaAs solar cells fabricated from molecular beam epitaxy (MBE) material. The efficiencies of cells fabricated from MBE material are now comparable with those fabricated from metal-organic chemical vapour deposition material, even for cells of dimension 2 cm x 4 cm. This paper reviews the progress in MBE cell efficiencies. Also discussed is the role oval defects play in GaAs diode and solar cell performance.

Overview of amorphous silicon photovoltaic module development

D. E. Carlson
Solarex Thin Film Division, 826 Newton-Yardley Road, Newtown, PA 18940, USA

Abstract

Amorphous silicon (a-Si) photovoltaic (PV) modules are generally manufactured in a single-junction p-i-n configuration and in sizes ranging from a few

square centimetres to about 4,000 cm^2. These modules are being used in a number of both indoor and outdoor low wattage (less than 20 W_p (peak watt)) applications, but have not found widespread use in most higher wattage power applications owing to relatively low stabilized conversion efficiencies (approximately 4-5 per cent). The recent improvements in the performance and stability of a-Si based multijunction modules indicates that these modules should soon start to appear in the higher wattage outdoor applications. When multi-junction modules are manufactured in totally automated facilities, the manufacturing costs should fall below $1 per W_p, and these modules should then start penetrating the grid-connected power generation markets.

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Solar energy: small-scale applications in developing countries
P. Vanderhulst, H. Lanser, P. Bergmeyer, F. Foeth and R. Albers, TOOL Foundation, Entrepotdok 68A, 1018 AD Amsterdam, the Netherlands.
ISBN 90 70857 19 7, 1990, 62 p.

This publication is aimed at people who are interested in finding out whether they can use solar energy for small-scale applications in their daily lives. Thermal applications such as water heating, drying and cooking, as well as electricity generation using small photovoltaic systems are discussed.

Detailed information is provided on the following:

- Solar driers: principles of drying with the sun's warmth, principle of the flat-plate collector with cover, different designs and constructions of solar driers, and practical tips;

- Warming water with solar energy; technology and applications, collector, storage water distillation, solar boiler, solar disinfector and sterilizer;

- Cooking with the solar energy; parabolic solar cooker and the cooking box;

- Electricity from the sun; solar cells, balance of system, PV-system characteristics, implementation and applications.

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Silicon carbide, published by Elsevier Advanced Technology in association with Mitchell Market Reports

Third edition comprises approximately 300 pages A4 size, containing 30 tables. Price: £695/US$ 1,182. ISBN: 1 85617 151 1. Available from: Elsevier Advanced Technology, Mayfield House, 256 Banbury Road, Oxford OX2 7DH, United Kingdom; Tel: +44 (0)865 512242; Fax: +44 (0)865 310981.

This report is a comprehensive state-of-the-art reference work, covering the various forms of silicon carbide; how they are made and by whom; what they are used for and why. World production, trade and consumption figures are presented, as well as prices for silicon carbide materials.

"Silicon Carbide" describes in detail the world trade of this material. About 50 per cent of world production of grain enters into international trade. Western Europe is both the largest importer and exporter of silicon carbide. Western Europe accounts for about 35 per cent of total consumption, Asia - mainly Japan and China - for about 25 per cent, North America for 20 per cent, the former Eastern Bloc for a little over 10 per cent, South and Central America for a little under 10 per cent.

World consumption of silicon carbide is described both by geographical area and end use. Unlike the consumption of silicon carbide grain, which is static, consumption of grits/powders, fibres and whiskers is growing and has considerable potential for further growth. It is in the field of composites that major growth will occur. Another success is the development of metal matrix composites reinforced with silicon carbide particulates.

This third edition of the report highlights the different forms and production methods for silicon carbide. A wide range of applications, both the traditional - refractories, abrasives, and metallurgical uses - and the newly established are covered in detail. Applications still under development are also discussed. Names of the companies and institutes involved in the manufacture and development of these applications are presented.

The report contains prices for grain as well as powders, fibres, whiskers, and components. The price for silicon grain varies considerably with grade, origin and quantity. It declined during the 1980s, due to overcapacity and exports of cheap material from some of the former Communist Bloc countries, Brazil, India and elsewhere. The average price for grain is approximately US$ 900 per ton. Prices for powders, fibres, etc. vary from tens to hundreds of US$ per kilogram.

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Advances in solar energy: An Annual Review of Research and Development; Volume 7
Edited by Karl W. Böer and published by the American Solar Energy Society. ISBN 0-89553-250-6.

Past Issues

Volume 6 - Sold out

Volume 5

Topics include: Amorphous silicon solar cells, Optical materials used in solar energy conversion, Prospects of Hydrogen technology, State of wind technology today, Potential for widespread retrofitting of solar conversion for existing homes, Architectural design in harmony with climate and the comfort of all occupants. Plenum Publishing, 1989

Volume 4

Topics include: Biomass for food and fuel, Lignin Hydrotreatment to low-molecular-weight compounds, Polycrystalline II-IV-related thin film solar cells, Design methods for earth-contact heat transfer, Central solar heating plants with seasonal storage, Salinity-gradient solar ponds. Plenum Publishing, 1988, 513 pages, illustrated.

Volume 3

Topics include: Thermosyphon solar energy water heaters, Production of terrestrial biomass for fuel use, Space heating (air system), Efficiency limits in solar cells, Physical theory of selective surfaces, Daylight research, Passive design for commercial buildings, Solar control, Advanced analytical techniques for materials and devices. Plenum Publishing, 1986, 482 pages, illustrated.

Volume 2

Topics include: Measurement of solar radiation, Anaerobic digestion of biomass, Lignocellulose pyrolysis, Earth contact buildings, Concentrating solar collectors. Plenum Publishing, 1985, 487 pages, illustrated.

Volume 1

Topics include: Biomass pyrolysis, Radiometry, Solar heating. Wind energy conversion. Ethanol production. Radiation standards and calibrations.

Also new from the American Solar Energy Society:

Proceedings of the 1992 Annual Conference

Edited by S. Burley and M. E. Arden
ASES 1992, 427 pages, illustrated.

Topics include: Photovoltaic Research and Development Activities; Solar Electric Testing, Evaluation and Development; Solar Electric Modeling and Design Issues; Field Experience: PV, Solar Ponds and Components; Utility Applications and Demand-Side Management; Active Solar DHW and Space Heating; Active Solar; Active Solar Components and Simulators; Active Solar: Cooking, Cooling, Distillation and Audits; Solar Collectors; Solar Fuels and Chemicals; Resource Assessment Analysis and Models; Resource Assessment Instruments and Data; Program and Environmental Issues; Implementation Issues and Program Overviews; Education.

Proceedings of the 17th National Passive Solar Conference

Edited by S. Burley and M. E. Arden
ASES 1992, 291 pages, illustrated.

Topics include: Passive Prediction Techniques; Passive Components; Passive Case Studies; Daylighting; Passive Cooling; Vernacular Architecture; Sustainability; Issues and Policy; Education.

Advances in Solar Energy		Non-member	Member
0-89553-250-6	Volume 7	$125	$112
0-306-43323-0	Volume 5	$125	$112
0-306-42810-5	Volume 4	$125	$112
0-306-42364-2	Volume 3	$125	$112
0-306-42064-3	Volume 2	$125	$112
0-306-42019-8	Volume 1	$125	$112
Proceedings of 1992 Annual Conference			
0-89553-164-X		$100	$50
Proceedings of 17th National Passive Solar Conference			
0-89553-207-7		$100	$50

Shipping is $3 per book in the US and Canada. To other countries, add 10 per cent for surface rate or 30 per cent for air rate.

Send to: *American Solar Energy Society, 2400 Central Avenue, Suite G-1, Boulder, Colorado 80301, USA; Tel: (303) 443-3130; Fax: (303) 443-3212*

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Solar Photovoltaic Products: A guide for development workers

Anthony Derrick, Catherine Francis and Varis Bokalders
IT Publications, London, 1991. 128 pages; Pbk; £12.50; ISBN 1-85339-002-X

A buyer's guide to systems for water pumping and treatment, lighting, refrigeration, communications, and various other applications. New revised edition containing updated information on prices and suppliers' addresses, as well as technical developments.

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Applications of Photovoltaics: Conference proceedings

Ed Robert Hill and M. M. Pearsall
Solar Energy Society, 1989.
Pbk;. £12.00; ISBN 0-904963-42-X

A comprehensive account of the many different ways in which PV systems can be implemented, with an emphasis on developing countries.

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Solar-Powered Electricity

Bernard McNelis *et al*
IT Publications, London, 1988.
122 pages; Pbk; £10.50; ISBN 0-946688-39-7.

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Amorphous silicon technology - 1991: symposium held 30 April - 3 May 1991, Anaheim, California, USA

Edited by Arun Madun *et al*, Pittsburgh: Materials Res, 1991. 884 pages; $64 (Materials Research Society Symposium Proceedings; Vol. 219) 620.1'93 TK7871.99 91-25627; ISBN 1-55899-113-1.

Contents: Stability; Optical devices; Structure; Thin film transistors; Microcrystalline silicon; Solar cells; Novel devices; Density of states; Growth; Interfaces; Transport; Indices.

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Glow-discharge hydrogenated amorphous silicon

K. Tanaka (ed.): 1989, Tokyo, KTK Scientific Publishers; Dordrecht/Boston/London, Kluwer Academic Publishers; ISBN 0-792-30309-1.

Since the initial achievement of substitutional doping in hydrogenated amorphous silicon (a-Si:H) in 1975, this material has grown to be one of the most important materials in electronics, having opened up several new applications of amorphous semiconductors such as thin film solar cells, field effect transistors, and image sensors. This rapid progress has obviously been supported by many scientific contributions accumulated during the past decad . There are two main issues today in a-Si:H technology: the physics of amorphous semiconductors, dealing with problems such as localization in disordered systems, and the chemistry of the film deposition associated with plasma CVD.

This volume describes the R&D efforts which have been made by one particular group in Japan, with emphasis on the above latter approach. It also presents recent experimental results on structural, optical, and electronic phenomena of the materials which have been obtained using several new experimental techniques. The book should be helpful to both students and scientists who are not experts in this area.

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Worldwide photovoltaics: Players, materials, technologies, markets and trends

A technical/economic analysis
A comprehensive report on developments in technology and markets for photovoltaics

In the ten years that BCC has been studying photovoltaics, the industry has developed from an embryonic start-up to a small-level, established industry - which nevertheless has a long way to go before realizing the dreams that have been a part of it over the past decade. The industry has grown despite the stop-and-go pace of government funding of R&D, changes in the emphases of funding, the successive granting and withdrawal of federal and state tax concessions designed to encourage commercial and residential installation, and the gyrations of the oil industry, one of its strongest competitors for utility-scale installations.

Some of the topics this comprehensive report examines:

- The Federal Role in Photovoltaic Development: Research programme results; Goals for single-junction solar cells; Federal spending; Tax credit programmes
- Materials: For photovoltaic cells: ribbon processes; Thin films: Developments in A-Si; Amorphous silicon in Europe; Cadmium telluride; Copperindium diselenide; Gallium arsenide; Recent developments from International Solar Electric Technology Corp., Boeing
- Photovoltaic concentrator systems; Utility PV systems; Utility photovoltaic projects; Utility connected residential photovoltaic systems; Solar cells for space use
- Photovoltaics in Japan: Amorphous silicon solar cells; Producers of solar-grade silicon; Goals, research, experimentation, pilot systems
- Other International Activity: The European Community; Industrial advantages in Europe; Other worldwide activities; International agreements
- New Products and Applications: Automobile cooling; Battery charging; Portable PV systems; Marine use of solar panels; Garden lighting units; Outdoor advertising; Telemetry and telephone channels; Solar-powered water electrolyzer; Stand-alone air conditioning units; Solar-powered weighing scales; Solar cells and the automobile; FM radio stations; Telemetry systems
- Markets: Company activities

Published: August 1987. Price: $1,950.00
Business Communications Co., Inc., 25 Van Zant Street, Norwalk, CT 06855-1781, USA. Tel: (203) 853-4266.

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Publication on plastics issued

A booklet prepared to help manufacturers design plastic bottles for recycling has been published by the Society of the Plastics Industry's Partnership for Plastics Progress.

The booklet, entitled *Design for Recycling: A Plastic Bottle Recycler's Perspective* discusses ways that plastic bottle designers and producers can match their packages with current reclamation technologies. It also suggests that members of the industry adopt specific design rules.

Copies of the booklet are available from the Society of the Plastics Industry in Washington.

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Artificial composites for high temperature applications

M. U. Islam, W. Wallace, and A. Y. Kandeil: 1985, National Research Council of Canada/Noyes Data Corp.; ISBN 0-81551-169-8.

This book reviews developments and advances in artificial composites for high temperature applications. The current level of activity in the field is assessed; outstanding problems and research directions for the future are identified.

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Component repair, replacement and failure prevention in light water reactors

K. E. Stahlkopf and L. E. Steele: Reprinted from *The International Journal of Pressure Vessels and Piping*; Vol. 25, Nos. 1-4; 1986, London/New York, Elsevier Applied Science; ISBN 1-85166-025-9.

This volume represents the fourth in a series of seminars devoted to a progressive evaluation of technological developments concerning the solutions to observed failures or to factors affecting the development of flaws which may lead to failures.

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Sixth international conference on composite materials - Second European conference on composite materials

F. L. Matthews, N.C.R. Buskell, J. M. Hodgkinson, J. Morton (eds.)
Vol. 1, 1987, London/New York, Elsevier Applied Science; ISBN 1-85166-112-3.

This book is Volume 1 of a six-volume set (ISBN 1-85166-118-2) devoted to the proceedings of ICCM IV combined with ECCM 2 held on 20-24 July 1987 at Imperial College of Science and Technology, London. This joint conference offered delegates a unique opportunity to be updated on recent progress in composite technology in both academic and research establishments.

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Low cycle fatigue and elasto-plastic behaviour of materials (Proc. 2nd Int. Conf.)

K.-T. Rie (ed): 1987, London/New York, Elsevier Applied Science; ISBN 1 85166 143 3.

The conference was held 7-11 September 1987 at the Arabella Conference Centre, Munich, FRG. Progress in various aspects of relevance to researchers and engineers was discussed.

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Modelling the flow and solidification of metals

T. J. Smith (ed.): Reprinted from *Applied Scientific Research*, 1987, Vol. 44, Nos. 1-2, additionally containing one review paper and an index; 1987; Dordrecht/Boston/Lancaster, Martinus Nijhoff; ISBN 9 0 2473 526 2.

The flow and solidification of molten metals is important in many metal processing operations. The mathematical modelling of these phenomena is complex due to the large range of scales encountered, ranging from the microscale of dendrites to the macroscale of large casting. Recent advances in computer technology, together with significant developments in metallurgy, now allow the realistic modelling of these processes.

This book brings together contributions from a number of authors, each a specialist in his field, which cover the whole spectrum of problems involved in the mathematical modelling of the flow and solidification of metals.

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Superplasticity in crystalline solids

J. Pilling and N. Ridley: 1989, London, The Institute of Metals, paperback, 210 x 148 mm, 214 pp., £18.00, US$ 36.00. ISBN 0 901462 56 X.

The literature on superplastic behaviour becomes increasingly more abundant displaying its widening utilization for commercial purposes and the widespread curiosity about its detailed mechanism. Although several informative reviews on aspects of superplasticity have appeared in edited volumes or in conference proceedings, the previous textbook on the subject by Padmanabhan and Davies was published in 1980 - a considerable time ago in a fast-moving field. About half of the references listed, out of a total of almost 300, in the new book by Pilling and Ridley, emerged within the last 10 years justifying the authors' intention of presenting a coherent and up-to-date view.

The book arose from lectures given to final year undergraduates and to graduate students at the University of Manchester Materials Science Centre. The text however is much more than a series of lecture notes, and concentrates on the area now known as "micrograin superplasticity". Words are not spared in achieving a firm thread of continuity throughout, with extensive descriptions of experimental procedures, microstructural development, mechanical behaviour, the appraisal of theoretical proposals and practical applications. There is also an abundance of information in clearly presented tables, line diagrams, and micrographs.

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Microstructural design of fibre composites

Chou, Tsu-Wei: NY: Cambridge University Press, 1992. 569 p. $150. 620.1'18 TA481.5 90-43347 ISBN 0-521-35482-X.

Contents: Thermoelastic behaviour of laminated composites. Strength of continuous-fibre composites. Short-fibre composites. Hybrid composites. Two-dimensional textile structural composites. Three-dimensional textile structural composites. Flexible composites. Nonlinear elastic finite deformation of flexible composites. indices.

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Constitution and properties of ceramic materials

Pampuch, Roman: NY: Elsevier, 1991. 456 p., $151.25 (Materials Science Monographs; 58).
620.1'4 TA455 89-27818 ISBN 0-444-98794-0.

Contents: The constitution of ceramic materials. The properties of ceramic materials. Tables of properties of ceramic materials. Subject index.

Note: Translated from the Polish edition, *Materialy ceramiczne*, first published in Warsaw in 1988. Discusses physical and chemical properties of ceramic materials, including potential applications of these materials in industrial and electronic devices and equipment. Additional topics include brittle fracture, dielectric materials, ferrites, orbitals, polarization, and resistance to thermal shocks. Charts and diagrams accompany the text. For university collections.

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The Elsevier Materials Selector is claimed to be the most comprehensive and up-to-date comparative information system on engineering materials and related methods of component manufacture. The 2,200 page, three volume publication has been edited by Norman Waterman of Quo-Tec and Michael Ashby, professor of engineering at Cambridge University. Volume one covers all aspects of the initial stages in solving a materials selection problem. Volume two covers the performance of metals and ceramics, while volume three covers plastics, thermosets, elastomers, composites and laminates. The Materials Selector costs £650.

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The Technology/Economy Programme: Technology in a Changing World
158 pages, OECD, Paris 1991. FF 180; £25; US$ 42; DM 75; ISBN 92-64-13598 7 (92 91 06 1)

This is the published version of a report prepared by a group of experts for the Secretary General of the OECD and transmitted to the OECD Council at Ministerial level on 4-5 June 1991. Drawing from the recommendations of this report, Ministers have, on this occasion, adopted a declaration (reproduced in the present report) on technology and the economy.

There is a general perception that new technologies, and in particular information and communication technologies, are having a profound impact on our economies and societies. The "globalization" of financial and goods markets, as well as increasingly of the enterprise structure, is in part a reflection of the impact of these technologies. Positive effects on productivity from the introduction of information and communication technologies have been demonstrated at the firm, or micro-economic, level. At the macro-economic level the connection between the spread of such new technologies and the growth of overall productivity has not, to date, been captured satisfactorily, perhaps reflecting the complexity of the aggregate economic system. (Organization for Economic Cooperation and Development (OECD), 2, rue André-Pascal, 75775 Paris Cedex 16. Tel. 45 24 80 89)

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Plasticity and high temperature strength of materials - Combined micro- and macro-mechanical approaches

M. Ohnami: 1988, London/New York, Elsevier Applied Science; ISBN 1 85166 119 0.

This book presents fundamental information on the plasticity and high temperature strength of structural materials as a result of a combined micro- and macro-mechanical approach to research, and will provide researchers, engineers, graduates and undergraduates of mechanical engineering, materials science and metallurgy, with a comprehensive understanding of important ideas and theories.

The information contained in this volume is presented in a logical and systematic manner and provides the fundamental concepts, methodologies, and applications to technology of current research in the field.

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New applications of materials

A. J. van Griethuysen (ed.): 1987, The Hague, Scientific and Technical Press; ISBN 0 95136 230 5.

This is a report in book form from the Netherlands Study Centre for Technology Trends (STT), translated for the FAST Programme of the Commission of the European Communities. It contains sections on new material applications, choice of material, case studies, and types of material.

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Advanced composite materials - Products and manufacturers

D. J. De Renzo (ed.): 1988, Park Ridge, NJ, Noyes Data Corp.; ISBN 0 81551 155 8.

Advanced composite materials are emerging as high performance materials for many applications. The materials range from the widely used reinforced plastics to the more recently developed metal matrix and ceramic matrix composites.

Information is provided on more than 800 products manufactured by the 74 US composite material manufacturers who supplied product data.

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How to apply advanced composites technology: proceedings of the Advanced Composites Conference, 1988, Dearborn, Mich., USA

Metals Park; ASM, 1988. 529p. $87.
620.1 TA418.9 88-071675 ISBN 0-87170-347-5

Contents: Economics of various processes. Energy management. Composite cure development. Manufacturing. Military. Flammability and smoke. Reliability property data. Fastening and joining. Liquid moulding. NDT & mechanical testing. Preform development. Design. Emerging materials. Recycling.

Note: Publishes 66 papers presented at an international advanced composites conference whose main focus was automotive applications. and in particular, automotive energy management utilizing composites. Additional areas covered are US military applications of composites to ground combat vehicle hull and turret structures, and forming technologies. Technologists, managers and planners from industry, academia and government are represented. No subject index.

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Superalloys, Supercomposites and Superceramics

Edited by John K. Tien and Thomas Caulfield (Academic Press, 1989), 755 pages; ISBN 0-12-690845-1.

This book consists of 22 chapters authored by experts in their specialties. It should be viewed primarily as a sampling of contemporary subjects in superalloy technology, insofar as 17 of the 22 chapters deal with various aspects of superalloy research and technology.

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Annual review of materials science

Vol. 19. Edited by Robert A. Huggins, Joseph A. Giordmaine and John B. Wachtman. Palo Alto: Annual Reviews, 1989. 562p. $66.
620.1'1'05 TA401 75-172108 ISSN 0084-6600 ISBN 0-8243-1719-X.

Contents: Experimental and theoretical methods. Preparation, processing, and structural changes. Properties and phenomena. Special materials. Indexes.

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Plastics materials: properties and applications

Arthur W. Birley, R. J. Heath and M. J. Scott: 2nd edition. NY: Chapman & Hall, 1988. 198p. $36.95. 620.1'923 TA455 88-4301 ISBN 0-412-01781-4.

Contents: Fundamentals of design. Styrene plastics. Other amorphous thermoplastics. Propylene plastics. Other polyolefin plastics. Other crystalline thermoplastics. Vinyl chloride plastics. Specialty thermoplastics. Cross-linked plastics. Polyurethane plastics. Index.

Note: Provides basic introduction to plastics technology for new and experienced readers. Revised and expanded since the first edition (1982) to cover new materials, technologies and design concepts. Discussion of thermoplastics touches on polymer blends and alloys, while chapters on thermosets reflect applications of phenolics and increasing significance of polyurethanes. Also discusses two-component process technologies. Includes figures, tables, photographs and a few references.

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Composite Materials Design and Analysis is based on the proceedings of the conference on computer-aided design in composite materials technology which was held in Brussels in April. It includes sections on fabrication techniques and simulation, advanced design techniques, finite element analysis, experimentation, failure analysis and optimization techniques. The 590-page hardback, which costs £79, is published by Computational Mechanics Publications of Southampton, UK.

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Design with Advanced Composite Materials is edited by Leslie Phillips, one of the three original co-inventors of carbon fibre. Each chapter is written by a leading expert on the different aspects covered, which include: fabrication; thermoset composite properties; pultrusion design; resin matrices; joining and finishing of composites; specifications and quality control; applications; and the mathematical aspects of designing with composites. The 365-page hardback is published by the Design Council in London, U.K. and costs £35.

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Composite Materials in Aircraft Structures, edited by Donald Middleton, covers the origin and potential of different types of composite materials, design rules, manufacturing, tooling, quality assurance, non-destructive testing and repair techniques. Case studies include the Airbus, Harrier, helicopter blades, propellers, braking systems and gas turbine engines. The 394-page hardback costs £45 and is published by Longman Scientific & Technical in Harlow, Essex, UK.

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The proceedings of the 11th International European Conference of SAMPE, which was held in Basel in May 1991, are now available to all. The 39 papers cover all types of composites, with contributions from Japan, the USSR, China, the United States and Europe. Areas covered include: high temperature and high toughness organic matrix composites; non-destructive testing; manufacturing for aerospace applications; and adhesives. The 545-page hardback is available from its editor, Howard Hornfeld of Consultex, which is based in Bogis-Bossey near Geneva, Switzerland. The book costs SFr 100.

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Advanced Composites, edited by Ivana K. Partridge, aims to provide a readable overview of advanced composites, primarily continuous fibre reinforced organic matrix materials. It also contains a brief look at inorganic matrices. Chapters cover raw materials, design, fabrication, damage tolerance, fatigue resistance and certification of civil aircraft composite structures. The 439-page hardback costs £68 and is published by Elsevier Applied Science, Barking, Essex.

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The third edition of Advanced Composite Materials: Directory of European Activities has been published by Metra Martech of London. The directory focuses on ceramic, metal and polymer-based composites and contains updated entries from more than 280 participating organizations from 14 European countries. They include suppliers of raw materials, semi-finished products and processing technology manufacturers, as well as research, testing and consulting organizations. The 310-page paperback, which also contains a reference section of 1,500 companies, costs £125.

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The proceedings of Fibre Reinforced Composites FRC90, which was held by the IMechE in March 1990, are available, price £65, from Mechanical Engineering Publications of Bury St. Edmunds, Suffolk, United Kingdom. The 35 papers cover a wide range of topics with a special emphasis on design for performance, thermoplastic matrix composites, and impact and compressive properties.

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The International Encyclopedia of Composites is a mammoth six-volume work edited by Stuart Lee of SAMPE. It contains approximately 6,000 pages, covers more than 250 subjects and features more than 3,000 illustrations and 1,000 tables. It is published by New York-based VCH Publishers, which has European offices in Weinheim, Germany. Each volume of the encyclopaedia costs DM 450.

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The UK Composites Industry Directory has been published by the Composites Processing Association of Crewkerne, Somerset. It includes a 16-page introduction on composites and a 42-page listing of the Association's 73 member companies and their activities. The directory costs £10 in the EEC and £12 elsewhere.

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1992 ECCM Composites Proceedings

EACM-2, place de la Bourse, 33076 Bordeaux Cedex, France. Tel.: +33 56 01 50 20, Fax: +33 56 01 50 05.

Developments in the Science and Technology of Composite Materials

5th European Conference on Composite Materials, 7-10 April 1992, Bordeaux, France. Edited by A. R. Bunsell, J. Jamet, A. Massiah. 1992 - 963 pages. Price: FF 1,200. ISBN 2-9506577-0-2

and

ECCM-CTS Composites Testing and Standardisation

European Conference on Composites Testing and Standardisation, 8-10 September 1992, Amsterdam, The Netherlands. Edited by P.J. Hogg, G. Sims, F.L. Matthews (BCS), A.R. Bunsell, A. Massiah (EACM). 1992 - 580 pages. Price: FF 1,200. ISBN 2-9506577-1-0.

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Surface modification technologies V

T. S. Sudarshan and J. F. Braza (eds.): 1992, London, The Institute of Materials, 902 pp., casebound, 160 x 230 mm, £99/$198. ISBN 0 901716 13 8.

This volume consists of the proceedings of the fifth in a series of international conferences organized by Dr. T. S. Sudarshan. The conferences are devoted to increasing the awareness of practical applications of surface modification technologies and their integration into manufacturing in various types of industries: the fifth was held in Birmingham during September 1991.

The contributions cover a wide range of technologies and applications, and commence with an important group of papers devoted to the subject of orthopaedic implants. These include papers by surgeons as well as scientists and cover not only the wear process and means of reducing it, but also the role of wear debris in prosthetic loosening. Other subjects particularly well covered are: sputter vapour deposition, with emphasis on mechanisms and structure and compositional control; diamond and diamond-like carbon films and their properties and potential; and laser processing, including cladding, alloying, and coating by means of pulsed excimer lasers.

The 68 papers presented are all of a high technical and scientific standard and include a number of important individual papers. The proceedings also provide the reader with a useful overall picture of where the frontiers of research and development are advancing. The emphasis is consequently on emerging technologies such as PVD and lasers, rather than traditional processes such as spraying, plating, carburizing, etc. The authors represent 16 different countries, although with a predominance from the USA, particularly in respect of orthopaedic implants.

The book contains a large amount of important material and will certainly repay close study. It is not, perhaps, particularly easy to flip through lightly, since there are no chapter headings and the page headings repeat the title of the book rather than giving any indication of the subject of a particular paper. There is, however, a very comprehensive 11-page subject index which enables the reader to find his way without difficulty. Indeed, use of the index is essential if one is to derive full benefit from this book since, for instance, an important review paper on diamond and diamond-like carbon films is grouped with tribological evaluation and one of the papers on laser processing appears in the miscellaneous group.

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Principles of the surface treatment of steels

C. R. Brooks: 1992, Basel/Lancaster, Technomic, 290 pp., clothbound, SFr 130. ISBN 0 87762 796 7.

Surface engineering has developed into one of the major fields in materials science and engineering, and now includes numerous processing techniques, associated with many fundamental and applied aspects across the spectrum of industrial materials. In ferrous metallurgy, the enhancement of specific properties of steel components such as resistance to wear, corrosion, and fatigue is commonly achieved through surface treatments. The wide range of processes available includes some with long established histories, such as carburising, and others introduced in relatively recent years, utilizing, for example, electron or ion beam techniques.

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European Advanced Inorganic Coatings Directory 1992
A guide to European manufacturers and suppliers of advanced inorganic coatings

A comprehensive and up-to-date information source on the European advanced inorganic (non-electrolytic) coatings industry. Over 200 pages featuring information from over 1,000 European suppliers of inorganic coating services and coated components, together with details of inorganic coatings research projects carried out by over 100 European research centres. Information on commercially-available products within the following areas is given in the directory:

- Metallic and ceramic plasma and flame spray coatings
- Chemical vapour deposition (CVD) and physical vapour deposition (PVD) thin films
- Vacuum metallization, sputtering, ion beam implantation, ion plating, and other advanced coating techniques
- Diamond and diamond-like thin films and other new developments
- Optical, optoelectronic and electronic coatings
- Wear resistant, heat resistant and corrosion resistant coatings
- Inorganic coatings for aero-engines and mechanical engineering
- Coated cutting tools and dies
- Raw materials and equipment for inorganic coatings production

Materials Technology Publications, 40 Sotheron Road, Watford, Herts. WD1 2QA, United Kingdom. Tel.: +44 923 237910, Fax: +44 923 211510.

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Advanced ceramic matrix, metal matrix and carbon-carbon composites
Current and Potential Markets

Dr. John Briggs: ISBN 1 871677 01 7

- Aerospace applications (aero-engine components, leading edge parts for hypersonics, brakes, airframe materials, others)
- Automotive applications (pistons and other automotive parts, turbine projects)
- Whisker reinforced cutting tools and wear parts
- World-wide markets and trends
- Future prospects
- Market forecasts for US and Western Europe to the Year 2000
- Fibre and particulate raw materials
- Major company profiles
- Health aspects
- Fabrication trends, property data and comparisons
- Industrial and academic research and development programmes
- Names and addresses of companies and research centres
- Over 150 pages, including 60 tables

Materials Technology Publications, 40 Sotheron Road, Watford, Herts. WD1 2QA, United Kingdom. Tel.: +44 923 237910, Fax: +44 923 225885.

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6. PAST EVENTS AND FUTURE MEETINGS

1993

22-28 April Washington, D.C.	Solar '93 - Solar Emerging: The Reality (American Solar Energy Society and US Dept. of Energy, American Solar Energy Society, 2400 Central Ave., Suite G-1, Boulder, Colorado 80301, Fax: 303-443-3212)
17-28 May Bangkok, Thailand	4th AIT-WHO Training Course on Solar Refrigerators Repair and Maintenance (Asian Institute of Technology, Division of Energy Techn., GPO Box 2754, Bangkok 10501, Thailand, Fax: 662 516 2126)
6-10 June Marrakesh, Morocco	First International Thermal Energy Congress (Cadi Ayyad University, Prof. A. Mir, Faculty of Science Semlalia, BP S15, Marrakesh, Morocco, Fax: 212 4 436769)
23-27 August Budapest, Hungary	ISES Solar World Congress (Prof. Laszlo Imre, Technical University, 1521 BME, Budapest, Hungary, Fax: +36 1 166 6808)

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17-18 March London	Plastics Recycling Recycling in the automotive, packaging and white goods sectors (Expotel Special Events, Kingsgate House, Kingsgate Place, London NW6 4HG, Fax: +44 71 624 6449)
23-26 March Dresden, Germany	Materials by Powder Technology (Deutsche Gesellschaft f. Materialkunde e.V., Adenauerallee 21, D-6370 Oberursel, Germany)
29-31 March Manchester, UK	Composite Materials (D. Schorer, Conf. Org., The Plastics and Rubber Institute, 11 Hobart Place, London SW1W 0HL, Fax: +44 71 823 1379)
13-17 April San Francisco, California	9th Internation Conference on Wear of Materials (Wear of Materials Secretariat COMST, PO Box 415, CH-1001 Lausanne 1, Switzerland)
26-30 April Vienna, Austria	Magnetics and Magnetism and Magnetic Materials (Institute of Electrical and Electronic Eng., 655 15th Street, Suite 300, Washington, D.C. 20005, USA)
17-19 May Aachen, Germany	Joining Ceramics, Glass and Metal (Deutscher Verband f. Schweisstechnik, Postfach 2725, D-4000 Düsseldorf 1, Germany)
24-28 May Reutte, Austria	Refractory Metals and Hard Materials - Key to Advanced Technologies (Metallwerke Plansee GmbH, A-6600 Reutte, Austria)
1-3 June Dortmund, Germany	2nd ASM Heat Treatment and Surface Engineering Conference (ASM European Office, rue de l'Orme 75, Olmstraat, B-1040 Brussels, Belgium, Fax: +32 2 733 43 84)
23-25 June Santa Barbara California	Electronic Materials (Minerals, Metals and Materials Society (TMS), 420 Commonwealth Dr., Warrendale, PA, 15086, USA)

6-9 September Tokyo, Japan	Computer-Assisted Materials Design and Process Simulation (Iron and Steel Inst. of Japan, Keidanren-Kaikan, 1-9-4-Otemachi, Chiyodaku, Tokyo 100, Japan)
'3-17September Madrid, Spain	European Ceramic Society - 3rd Conference (Sociedad Española de Ceramica y Vidrio, C. Ferraz, 11, 3 Dcha., 28008 Madrid, Spain)
20-24September Houston, Texas	Corrosion (National Association of Corrosion Eng., PO Box 218340, Houston, TX 77218, USA)
20-24September Clausthal, Germany	10th International Conference on Textures of Materials, ICOTOM 10 (Inst. of Metallkunde und Metallphysik d. Technische Universität Clausthal, Grosser Bruch 23, D-3392 Clausthal-Zellerfeld, Germany, Fax: +49 5323 72 23 40)
20-24September Bordeaux, France	HTCMC - High Temperature Ceramic Matrix Composites (Ms. D. Doumeingts, EACM, 2, place de la Bourse, 33076 Bordeaux, Fax: +33 56 01 50 05 or Prof. R. Naslan, LCTS, Domaine Universitaire, 3, allee de la Boetie, 33600 Pessac, France, Fax: +33 56 84 12 25)
26-29September Budapest, Hungary	EUROSENSORS VII Organized by the Technical University of Budapest and sponsored by Roland Eötvös Physical Soc. IMEKO and National Committee for Techn. Development (Technical University of Budapest, Dept. of Atomic Physics, Budafoki ut 8, H-1111 Budapest, Hungary)
29 September - 2 October Tokyo, Japan	6th International Confference on Ferrites (Prof. M. Naoe, ICF 6, Dept. of Physical Electronics, Tokyo Institute of Technology, 2-12-1, O-okayama, Meguro-ku, Tokyo 152, Japan)
12-15 October Göttingen, Germany	4th European Conference on Laser Treatment of Materials Materials Structure and Properties after Laster Treatment (Deutsche Gesellschaft f. Materialkunde e.V., Adenauerallee 21, D-6370 Oberursel, Germany)

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Advances in Materials Technology: Monitor

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