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# Solar Photovoltaics: Research, Manufacture and Application to Electric Power Systems*

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A photovoltaic (PV) electric generation system consists of groups of photovoltaic cells (more commonly known as solar cells) encapsulated for environmental protection into solar modules, and the balance-of-systems (BOS) components such as land, support structures, wiring, batteries and battery housing, alarm systems and, if needed, power conditioners to produce alternating current electricity. Solar cells (Fig. 1) represent the heart of any photovoltaic system. They are produced from semiconductor materials by photons contained in sunlight. This charge can be caused to flow and can be drawn off through externally connected wires.

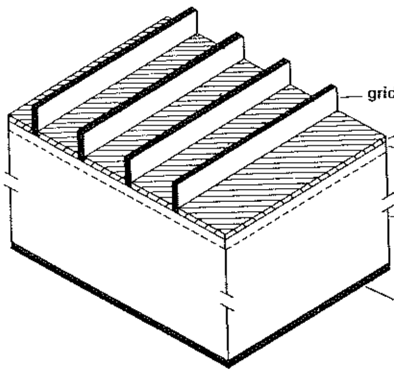


Fig. 1 Schematic diagram of a silicon P-N junction solar cell. The rectifying junction between the P doped and N doped regions causes carriers released by the light in the semiconductor to flow in the same direction and through any electrical load connected between the grid top contact and the ohmic rear contact.

Photovoltaic energy systems are a particularly attractive energy alternative which could play a significant role in the future energy production of many nations. The energy source used by all solar energy systems – sunlight – is free and inexhaustible, but photovoltaic systems are unique in that they convert sunlight directly into direct current electricity. In addition, these systems may have no mechanically moving parts, have potentially long lives, require little maintenance, and are generally without adverse environmental consequences.

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The terrestrial photovoltaic industry is now worldwide and not yet 10 years old. Technological changes are still occurring and will continue to do so for some time yet. The potential for further major cost reductions exists, and these will mean that opening of more markets to photovoltaics. Presently photovoltaic systems economically replace primary batteries, gas generators, thermoelectric generators and small petrol/diesel generators for, principally, remote area applications. This paper will assess the status of photovoltaic technology, the markets and the economics of PV systems, and the design of solar electric power systems.

## WILL THE TECHNOLOGY MEET THE COST GOALS?

### *Silicon sheet*

Most solar cells made today use circular, monocrystalline silicon (Si) wafers. These are produced from semiconductor grade Si material grown into large cylindrical crystals using the Czochralski process (Fig. 2), the wafers being finally sliced off the main crystal. Recognizing that the cost of these Si wafers is prohibitive for low cost PV, large R&D programs in this area were implemented some years ago in the US, Europe and Japan. These programs were aimed at developing processes which would produce "terrestrial solar grade (TSG)" Si in sheet form at low cost. An excellent review of the competing technologies can be found in Dietl, 1981. One important point that was verified early in these programs is that solar cells do not need the same level of purity or crystallinity necessary for the microelectronics industry. Therefore the thrust of the R&D programs is towards TSG Si to produce polysilicon wafers.

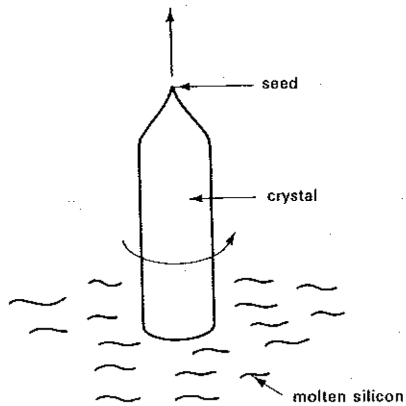


Fig. 2 The Czochralski growth of single crystal silicon ingots from the melt.

Looking at the R&D done in this area, one can gather that processes for low cost production of Si sheet already exist. Their implementation has commenced and a few manufacturers are selling potentially low cost sheet Si commercially. Si sheet prices will fall considerably through the rest of this decade as these new technologies are utilized and volume of Si used increases. Wacker Chemitronic, as an indication, expects to have 100 mm square polysilicon wafers available for \$1.25 in 1985/6 and \$0.66 in 1990 (Dietl, 1981). Other companies may well be ahead of these targets.

## *Cell processing*

The cell processing technologies in use today differ most markedly in the type and method of application of the metallic contacts to the Si. Differences also exist for surface preparation, diffusion, edge junction removal and anti-reflection methods, but any of these are usable with any one of the contacting processes. The three ways of applying the contacts are: (a) vacuum evaporation (Roy and Pschunder, 1981) which is generally considered the slowest and most expensive method; (b) electroless plating (Petersen and Muleo, 1981) which is low cost and reasonably common; and (c) screen printing (Godfrey and others, 1982; Mardesich and others, 1980) which is a proven low cost procedure and the most commonly employed.

In reality, the cell production processes/equipment required for low cost, very high volume production are in use today. Some manufacturers have already installed several megawatt (peak) capacity cell production facilities in anticipation of the ever increasing sales which are occurring. While process refinement for these Si sheet to solar cell technologies will certainly take place, no major changes to cell processing methods are expected, although more integrated production facilities (for example, ribbon Si feeding into a very high efficiency cell production process) may well emerge.

## *Module production*

Having produced the solar cells at high volume for a low cost, they must be protected from the very harsh terrestrial environment in which they will be placed. Typically many cells are strung in series/parallel connection before they are encapsulated into modules. These modules are, in turn, expected to have a 15-20 year life in operation in the harsh terrestrial environment. Similar to cell production, module designs and production processes/equipment required for low cost, high volume production are in advanced development today. Again some manufacturers are already using such equipment in large facilities. The most pressing problem remaining for the new module designs and materials entering the market is their reliability. In response to the need to try and determine if a module design is suitable for long life, various countries have proposed standards for module testing that will attempt to determine their suitability.

## *Balance-of-systems components*

Having produced the solar modules, they must be incorporated into systems. The modules must be mounted on a supporting structure (generally a metallic frame) to form a solar array. They must be wired together and to the electrical storage (generally batteries) and/or load. Included along this wiring may well be a regulator to control the charge to the electrical storage, a monitoring/alarm system for checking and fault indication and a power conditioner if the load requires ac power or precisely controlled dc power. Added to the above must be housing for the batteries and/or electrical components. Not all, however, of the above balance-of-systems components are necessary for all applications.

## *Future photovoltaic technology*

The photovoltaic technology which will ultimately prevail will be a thin film technology. In this approach, the semiconductor material is not self-supporting as in current silicon technolo-

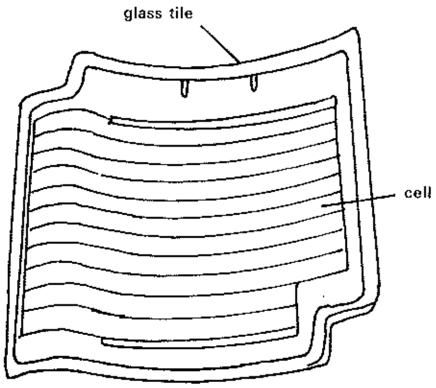


Fig. 3 An example of a thin film technology. Shown is a glass tile with a very thin amorphous silicon layer deposited comformally on its underside. The tile is a developmental prototype for residential system.

gy, but is deposited in a very thin film upon a supporting substrate such as in the case of the glass roof tile of Fig. 3. Traditionally cadmium sulphide cells have represented the most advanced thin film technology.

However, production and stability problems still remain for these cells. The strongest thin film technology at present is that based on amorphous silicon. The major impetus in this field has come from the Japanese (Hamakawa, 1982) and they have existing outdoor demonstration installations up to 2 kilowatts (peak) (Kuwano and others, 1982).

Notwithstanding the above, there have recently been some outstanding research achievements by the University of New South Wales Solar Photovoltaic Research Group which will prolong the competitive life of cells produced on single and polycrystalline substrates. They have

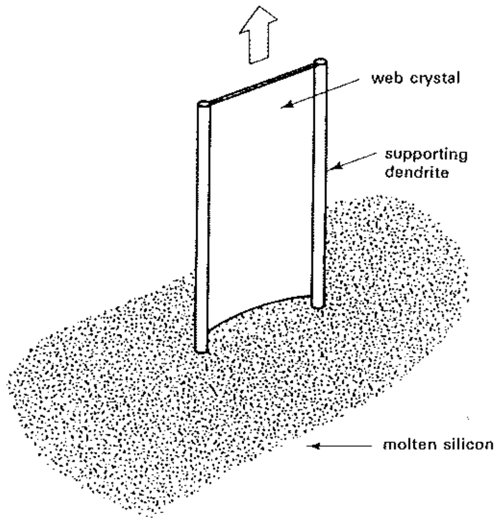


Fig. 4 The growth of high quality dendritic web silicon from the silicon melt. In this process. silicon is produced directly in the form of a crystalline sheet. The process is compatible with producing high efficiency cells at potentially low cost.

developed processes which have produced world record efficiencies of greater than 19% (under terrestrial sunlight) on silicon single crystal material. Combined with a high quality silicon ribbon material such as Westinghouse's dendritic web (Fig. 4) or Motorola's ribbon-to-ribbon, such a commercial technology could be viable for another 10-20 years. At the least it could provide a new stimulus to concentrator systems. The UNSW group is also carrying out R&D into polycrystalline silicon cell processing. Some recent results from new and innovative ideas show great promise for low cost and high efficiency cells on this material.

## MARKETS FOR PHOTOVOLTAIC SYSTEMS

Photovoltaic systems have widespread applicability and can be used virtually anywhere to produce electricity. Currently, however, the cost of such systems is too high to permit their economic use in other than remote-area applications. These include telecommunications, aids to navigation and, increasingly, water pumping, water purification and village lighting. However, various countries have sponsored large PV demonstration programs to assist their developing PV industry. These programs are continuing and initially provided a base load for the manufacturing facilities involved.

Such programs together with favourable tax incentives have led, for example, to Arco Solar's installation of a 1 MW (peak) system in 1982 to supply grid electricity in what is described as a commercial venture with Southern Californian Edison Company, a Californian electricity utility (Green and others, 1982). More such systems are planned in the US, for example, the Sacramento Municipal Utility District's planned installation of 100MW (peak) of PV systems in 10 stages over the next 12 years (SMUD, 1982). The first megawatts of this system are now being installed. Another ARCO venture with Pacific Gas and Electric has been 4.5 MW of the first 6 MW of a planned 16 MW installed by now.

With these remote area, large utility and demonstration systems predominating, market growth over the last few years has been consistently high. In 1981, an estimated 5 MW (peak) of PV modules was produced worldwide (US GAO 1982) with an expected world production level of 8-9 MW (peak) in 1982 (US GAO 1982; "Silicon . . .", 1982). Recent indications are that the market is now over 20 MW per annum worldwide and nearly 500 kW for Australian companies.

## COST PROJECTIONS OF PHOTOVOLTAICS

While it is now acknowledged that the original US Department of Energy cost and production goals will not be met, nor would they have ever been likely to (US GAO 1982), price reductions and increasing production levels will continue through the rest of this decade. Maycock ("Silicon . . .", 1982) predicts a production level of 500 MW (peak) in 1990 which has a realistic chance of being achieved.

An examination (Godfrey, 1982) of present and future costs reveals that solar modules should be able to be sold with a profit for \$9-\$10 per watt (peak) in 1982, \$4.50-\$5.50 per watt (peak) in 1986 and \$2.50-\$3.50 per watt (peak) in 1990 (in constantly 1982 dollars). The latter figure corresponds to a sales volume of 500 MW (peak) per year. These dollar figures are far higher than the original US Department of Energy goals, but are realistic. To achive these figures, large plants (25-50 MW (peak) capacity) working near maximum capacity will be required. It therefore seems probable that only a relatively small number of cell-module manufacturers worldwide will emerge, and Australia will likely have only 1-2 of these.

The balance-of-system costs even today can represent 50% of the total system cost. Unfortunately, as solar module prices continue to fall, BOS component costs do not show the same trend. Without commensurate BOS cost reductions, PV systems will not become truly competitive. Undoubtedly volume production will bring some savings, but new designs utilizing fewer and/or cheaper materials, yet retaining reliability, will be needed. Certainly it seems there will be room for more smaller, specialist systems manufacturers to utilize the product of the large module manufacturers. Innovation in BOS components and total system design is needed now.

## CONCLUSIONS

Photovoltaic modules and systems will continue to drop in price through the next decade. This will be due primarily to technology developments and market expansion. Some of these technology developments are occurring in Australia which means a possible growth of our present small industry to economically service its Australian and near-neighbour markets. While much emphasis is being placed on high volume, low cost module manufacture, more attention needs to be focused on balance-of-system components and their cost. The market is growing, and it is feasible for an Australian industry to be viable. It remains to be seen if this will be the case in five years time.

## REFERENCES

Dietl, J., D. Helmreich, and E. Sirtl (1981), *In crystals: growth, properties and applications,* Vol. 5, Springer-Verlag, Berlin.

Godfrey, R.B. (1982), The state of the art of solar cells, *Proc Symp on Technology and Economics of Solar Electricity Generation,* ISES/ANZ Sect (Vic Branch), Melbourne.

Godfrey, R.B., S.R. Wenham, M.C. Pitt and C.L. Kolila (1982), An advanced solar cell production line based on LSSA funded processes. *Conf Rec, 16th IEEE Photovoltaics Specialists Conf,* San Diego.

Green M.A., and others (1981), The MINP solar cell – A new high voltage, high efficiency silicon solar cell, *Conf Rec,15th IEEE Photovoltaic Specialists Conf,* Orlando.

Green, M.A. (1982), Survey of large photovoltaic systems in the megawatt to multi-megawatt range, *Proc, ISES/ANZ Annual Conf,* Brisbane.

Hamakawa, Y. (1982), Amorphous semiconductor technologies and devices, *Japan Annual Rev in Electronics, Computers and Telecom,* Ohmsha and North-Holland, Japan.

Kuwano, Y., and others (1982), A 2 kW photovoltaic power generating system using amorphous silicon solar cells, *Conf Rec, 16th IEEE Photovoltaic Specialists Conf,* San Diego.

Mardesich, N., and others (1980), A low-cost photovoltaic cell process based on thick film techniques. *Conf Rec, 14th IEEE Photovoltaic Specialists Conf,* Orlando.

Petersen, R.C., and A. Muleo (1981), Silicon solar cells with nickel/solder metallization, *Proc. 3rd E.C. Photovoltaic Solar Energy Conf,* D. Reidel Publishing Co, Holland.

Roy, K., and W. Pschunder (1981), Comparison of solar cells from nonsingle and single crystalline silicon in a pilot production line. *ibid.* "Silicon to Dominate PV Market into 1990, Maycock Tells ASES", 1982. *Solar Energy Intelligence Report,* 8 (24).

SMUD 100MW Photovoltaic Power Plant: Draft (and Final) Environmental Impact Report (1982), *California Energy Commission and Sacramento Municipal Utility District,* February (and April).

US General Accounting Office, 1982. Probable impact of budget reductions on the development and use of photovoltaic energy systems. Report EMD-82-60.