

## **Solar Electricity and Recent Progress in Thin Film Photovoltaics\***

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### *Abstract*

Current methods of producing electricity from solar energy are summarized. The role of photovoltaics is described and the increasing importance of thin film technology. The photovoltaic industry is doing well over \$10<sup>8</sup> worth of business in 1984 with a growth rate of about 50% p.a. Already over 15% of the output is in the form of thin films, practically all as amorphous hydrogenated silicon. A number of other thin film systems are being actively explored, most of them semiconductor heterojunctions, including CdS : Cu<sub>2</sub>S and CuInSe<sub>2</sub> : CdS. The problems of durability and cost effective production are yielding under major research and development efforts on thin semiconductor films and interfaces.

### **1. Introduction**

The production of heat from solar energy is a well established technology, with the heating of water a viable industry in a number of countries including Australia. However, the conversion of solar energy to electricity is a more difficult and less efficient process, although highly desirable in reducing use of fossil fuels for electricity production. Fossil fuel combustion continues to increase the concentration of CO<sub>2</sub> in the atmosphere with its attendant 'greenhouse' effect on Earth surface temperatures. There are three major methods of producing electricity from the Sun. The first two use solar fuelled heat engines to operate conventional type generators. The engines are either relatively small distributed ones, with their individual collector systems, or else a large central one can be used, operated from the heat collected at a focal point in a tall tower from a field of tracking mirrors. Current details of large demonstration projects based on both types are given in Tables 1 and 2 (see Lehner 1983). The 'power tower' systems so far installed are larger, but the final results on durability and real long term cost of the power produced are still being investigated. Efficiencies are generally in the range 5–15%. Larger systems are being planned.

The third system of electricity production involves photovoltaics (PVs), whereby incident sunlight produces voltage and current from a semiconductor device without any moving parts. At first sight the technique appears fundamentally different from the other two approaches, but it is possible to view the process as one where an electron group is 'heated' (raised in energy) by the incident photons and then decays, i.e.

\* Paper presented at the Australia–New Zealand Condensed Matter Physics Meeting, Pakatōa Island, N.Z., 8–10 February 1984.

Table 1. Large distributed collector systems

Location	Nominal power (MW)	Type of engine	Cooling	Gross electric power (kW <sub>e</sub> )	Parasitic power (kW <sub>e</sub> )	Net efficiency (%)
Getafe (Spain)	0.05	1 stage screw expander	Water	30	3	5.4
Mali	0.05	3 screw engines	Water	51	—	2
Corsica (France)	0.1	2 turbines	Water	91	6.4	9
Meekatharra (Australia)	0.1	2 stage screw engine	Air	100	16	7.7
Sulaibyah (Kuwait)	0.1	Turbine	Air	129.4	31	13
Las Barrancas (Mexico)	0.1	2 stage screw expander	—	117	17	6.5
Coolidge (USA)	0.15	1 stage turbine	Water	103	28	4
Shenandoah (USA)	0.4	4 stage turbine	Air	500	100	14.5
Almeria (Spain)	0.5	7 stage turbine	Water	577	77	10.1
Nio (Japan)	1.0	8 stage turbine	Seawater	1000	160	9.6
Dead Sea (Israel)	5.0	Solar pond turbine	Water	—	—	2.0

Table 2. Large central receiver systems

Location	Nominal power (MW)	Number of heliostats	Reflective area (m <sup>2</sup> )	Type of engine	Cooling	Gross electric power (kW <sub>e</sub> )	Parasitic power (kW <sub>e</sub> )	Net efficiency (%)
Almeria (Spain)	0.5	93	3655	5 piston	Wet	599	99	16.5
Nio (Japan)	0.8	807	12912	Turbine	Wet	1000	200	8.5
Adrano (Italy)	1	Two types 70 and 112	6216	Turbine	Wet	1200	200	16
Almeria (Spain)	1	300	11400	Turbine	Dry/Wet	1200	200	12.5
Targasonne (France)	2.3	201	10740	Turbine	Dry	2500	200	20.6
Barstow (USA)	10	1818	72538	Turbine	Wet	12000	2000	15.3
Lenino (USSR)	5	1600	40000	Turbine	—	—	—	—

converts its energy to work in flowing round a circuit before returning to the ground state. This concept enables comparison with the working fluid of a heat engine. However, the coupling of the ‘working fluid’ to a generator to produce electricity

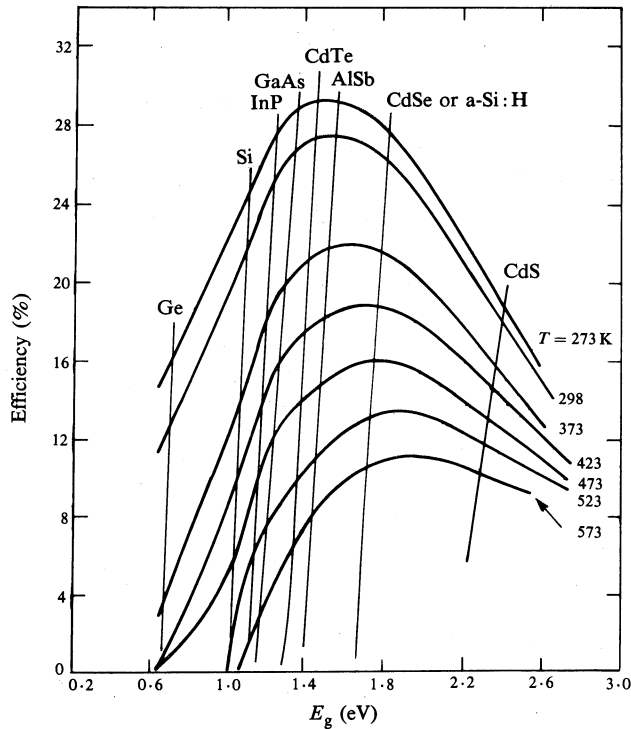


Fig. 1. Theoretical maximum attainable efficiency of a homo-junction solar cell as a function of bandgap energy for different temperatures. [From Wysocki and Rappaport (1960).]

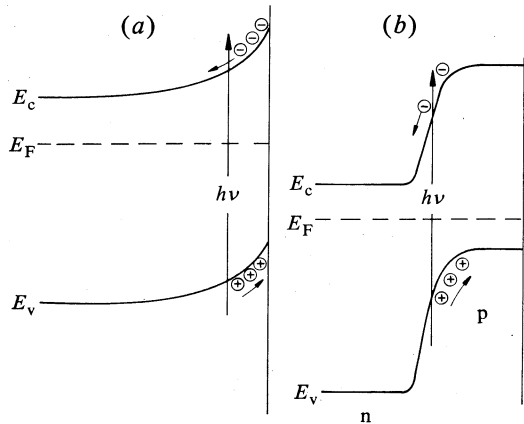


Fig. 2. Spatial variation of band edges with distance for (a) a surface (Schottky) barrier and (b) a surface p layer in n-type semiconductor, showing the drift of photoexcited carriers.

is not needed. Since the effective temperature of the excited electrons is very high, over  $10^4$  K, the efficiency, using Carnot’s principle, should be very high. However, the whole population of electrons is not excited, unlike the case of the

working fluid in the Carnot cycle, so that the net efficiency is much lower than that from direct application of the Carnot formula.

A mechanistic calculation of ideal efficiencies for various semiconductors as a function of their bandgap  $E_g$  is shown in Fig. 1. Here the distribution of photon energies found in the solar radiation at a portion of the Earth's surface at normal incidence has been taken into account. The term 'air mass 1 or AM1' refers to these conditions, with the air clean and dry, having 97% of the solar energy in photons with energy below 3 eV. The calculation considers excitation of electrons from the valence to the conduction band of a semiconductor, as in Fig. 2, and hence the size of its energy gap is important. The excited electrons begin to drop back to the valence band, i.e. to recombine with holes in the valence band, either directly or indirectly through intermediate states in the bandgap. The key to successful PVs is to separate the electrons from the holes so that they must go through a circuit before returning to their equilibrium energies in the valence band. This is done by providing an inbuilt electrical field in the illuminated region, either from charge trapped at the interface between the semiconductor and a liquid or metal contact (the Schottky barrier case) or from charge trapped between regions of different doping (the p-n junction case). Without going through the details of the calculation in this paper, one can appreciate that while a smaller bandgap semiconductor such as germanium ( $E_g = 0.65$  eV) will be energized by more photons in the solar spectrum than say silicon ( $E_g = 1.1$  eV), the excited electrons in Ge can drop in energy through the conduction band to within 0.65 eV of the holes so that the available energy for going round a circuit is less than for Si. Hence the net energy available per electron is less. These and related considerations lead to the curves in Fig. 1, where ideal material parameters have been assumed.

Table 3. Large photovoltaic systems

Location	Size (MW)	Location	Size (MW)
Phoenix (Ariz.)	0.24	Hesperia (Cal.)	1.0
Pellworm Is. (Medit.)	0.3	Sacramento (Cal.)	1.0 <sup>A</sup>
Saudi Arabia	0.35	Bakersfield (Cal.)	6 <sup>B</sup>

<sup>A</sup> Size is to increase to 100 MW. Price per peak Watt is \$4.95 (in 1982 US\$), reducing to below \$3.

<sup>B</sup> Size is to increase to 16 MW. Price per peak Watt is \$6 (in 1982 US\$) and reducing.

Although Si does not have the theoretically ideal bandgap of about 1.6 eV, its material properties, improved as a result of its intense development for circuit elements, are so good that it is the most widely used PV material, with commercial efficiencies mostly in the range 8–12%. Recombination centres, which cause electron-hole recombination despite the electric field, can be kept low in concentration and commercial solar cells have now demonstrated many years of reliable operation both on the surface of the Earth and in space. This has led to sufficient confidence in them for large scale power stations to be constructed recently, not just for demonstration purposes but also for feeding useful power into the grid systems of electricity supply organizations. Table 3 lists six large PV systems that have been constructed, all using crystalline Si cells. The last three are in California where a system of state and federal tax credits and concessions improves the apparent economics of the

installation of PV cells. The Sacramento Municipal Utility District is committed to the installation of 100 MW of PV supply in the next decade. The selling module price of just under \$US 5 per peak Watt (i.e. a size sufficient to produce 1 W at peak insolation, here about 5 cents per  $\text{cm}^2$  of finished cell) represents a remarkable cost reduction by an order of magnitude from prices prevailing in 1974 when the so-called energy crisis, triggered by a sudden steep rise in the price of oil, focussed much attention on non-fossil sources of power. It is argued that government subsidies for research and development, and purchase of production for reasons other than economic

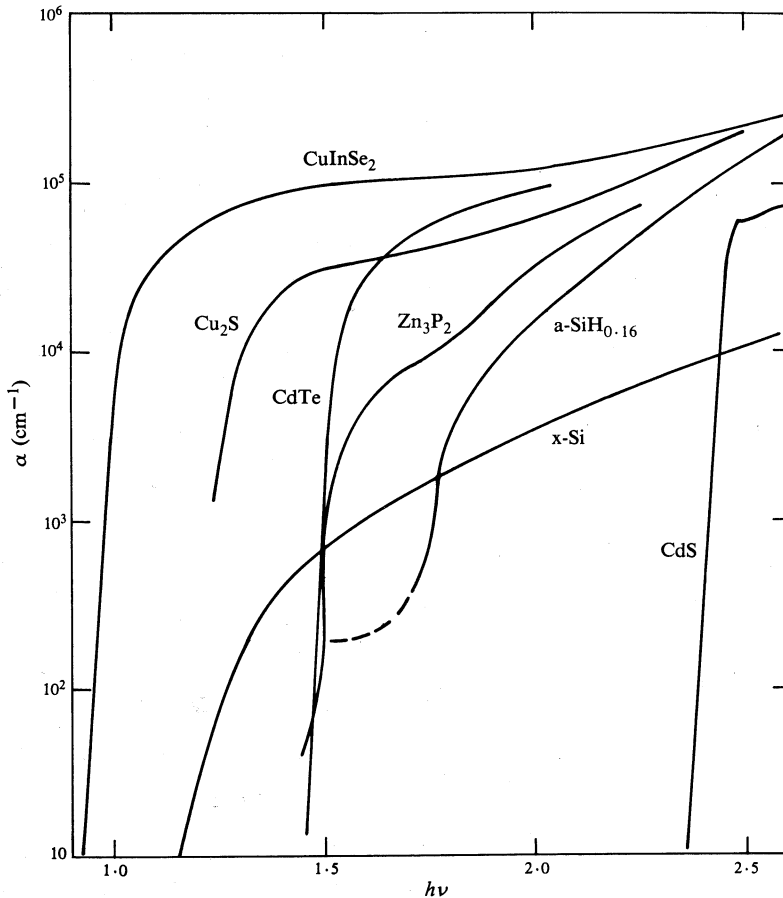


Fig. 3. Optical absorption coefficient  $\alpha$  for various highly absorbing compound semiconductors, as well as crystalline and amorphous hydrogenated silicon. [From Hermann *et al.* (1982).]

ones, should be taken into account in assessing the true costs of PV systems. While this is difficult to quantify, it appears that real costs are possibly now in the region of \$7–12 per peak Watt for large scale production. This is still too high by a factor of about 20 to make PV electricity competitive on unsubsidized terms with that from current coal fired generating stations. However, the costs of the latter continue to rise while PV system costs reduce. In addition PV systems have the very important advantages of being non-polluting and consuming no non-renewable resources, so that their future appears strong, accounting for the growth of the industry.

The discrepancy in cost between electricity from Si PV cells and from coal fired stations has stimulated an intense effort not only to reduce the production costs of Si (crystalline and polycrystalline) cells, but also to develop alternative PV systems. Silicon is an indirect bandgap semiconductor, which means that absorption of light at the threshold requires phonon assistance, resulting in a relatively slowly rising spectral absorption curve, as shown in Fig. 3. Hence the Si slices should be 20–40  $\mu\text{m}$  thick; this requires material to be sawn from ingots or grown as strips of this thickness. However, to produce areas as large as several hectares at low cost, it is likely that one will require techniques that can produce large area layers on a continuous production line basis, which strongly suggests a thin film technique. Continuous thick layers of crystalline Si have been produced, but their cost effectiveness has not displaced that of slices sawn from ingots. Silicon is not suited for thin layers, but there are some materials that have direct bandgaps and steeply rising absorption curves so that most of the sunlight can be absorbed within about 1  $\mu\text{m}$  of the surface. Furthermore, these materials will have to lend themselves to the above requirement of continuous film production at an overall low cost, and demonstrate an ability to function at reasonable efficiency over many years.

**Table 4. Reported efficiencies of polycrystalline thin film solar cells**

Material (window/absorber)	Absorber bandgap (eV)	Best effi- ciency (%)	Area ( $\text{cm}^2$ )	Comments
Si poly slices	1.1	~14	> 50	Production
n-(Cd, Zn)S/p-CuInSe <sub>2</sub>	1.0	11	1	Simulated AM1 solar spectrum, ELH lamp at 25°C <sup>A</sup>
n-(Cd, Zn)S/p-Cu <sub>2</sub> S	1.2	10.2	1	Cu <sub>2</sub> S formed by ion exchange <sup>B</sup>
pn-GaAs	1.4	9	1	p <sup>+</sup> /n/n <sup>+</sup> all-GaAs homojunction <sup>C</sup>
n-ITO/p-CdTe <sup>E</sup>	1.5	7.3	1	CVD deposition <sup>C</sup>
CdSe	1.7	6	3	PEC cells <sup>D</sup>
n-CdS/p-Cu <sub>2</sub> Se	1.2	5.4	1	Note <sup>A</sup>
Mg/Zn <sub>3</sub> P <sub>2</sub>	1.5	4.3	1	Schottky barrier <sup>B</sup>
CdS/CdTe	1.5	12.8	0.78	Screen printed <sup>F</sup>

<sup>A</sup> Boeing. <sup>B</sup> Institute of Energy Conversion (USA). <sup>C</sup> Southern Methodist University (USA).

<sup>D</sup> Photoelectrochemical. <sup>E</sup> Indium tin oxide (ITO). <sup>F</sup> Matsumoto *et al.* (1984).

These requirements are severe, and are obviously a challenge to semiconductor film technology. A large and developing effort is now being devoted to a variety of thin film systems; Table 4 lists some of them. At the present time none (except Si) are actually in commercial production for the purpose of generating general solar power, although demonstration modules have been produced. However, amorphous hydrogenated silicon is in large scale commercial production in Japan (more than 2 MW per annum) for power cells integrated into consumer electronic items such as watches and calculators, and this is probably the system closest to commercial application for general PV power.

It has been stated that, even for free PV cells, a minimum conversion efficiency of 10% is required in order to achieve an overall system cost for PV power in the region of 5 cents per Watt. This calculation is based on certain assumptions about costs of land and support structures. If the PV panels are placed on rooftops, eliminating land costs and reducing structure costs, then one can show that this minimum

efficiency is around 5%. Of course it becomes lower still if the target price of 5 cents per Watt is raised, as is already occurring due to increasing costs of electricity from the competing fossil fuels. This consideration means that relatively inefficient PV systems can be important if they can be produced sufficiently cheaply. (For example, the average useful conversion efficiency of solar energy incident on a field of crops is around 1%, and around 0.1% for production of meat.) Although Si crystal PV systems can have efficiencies greater than 10%, the cost requirement is the current stumbling block. The system which eventually proves successful is likely to be one which keeps costs low without sacrificing too much efficiency, and in the remainder of this paper we consider some of these systems of interest.

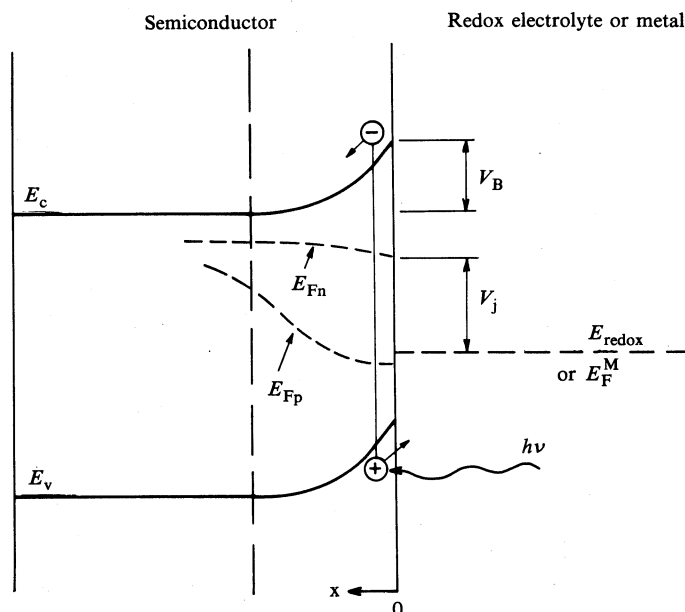


Fig. 4. Energy band edges and electron and hole quasi-Fermi levels for an n-type semiconductor in contact with an electrolyte or metal during current flow. The quantity  $V_B$  is the surface barrier height during current flow and  $V_j$  is the photovoltage developed at the interface. [From Haneman and McCann (1982).]

## 2. Cuprous Sulfide Heterojunctions

One of the earliest PV thin film systems was CdS:Cu<sub>2</sub>S heterojunctions, modules of which were marketed recently with an efficiency of 3–5% (Chopra and Das 1983). However, they turned out to show decay after about six months for various reasons, including Cu diffusion and inadequate hermetic sealing against water vapour. The production process involved up to 20 steps and whether the eventual cost reduction would be sufficient remained in question. Laboratory systems have now been produced with peak efficiencies close to 10% and it has been stated that the problems of long term stability have been solved (K. W. Boer, personal communication). However, the competitive position of this system compared with others is sufficiently doubtful that despite investments of several millions of dollars, marketing is not proceeding.



More remarks about heterojunctions are made in Section 5 in reference to  $\text{CuInSe}_2$ :CdS systems.

### 3. Cadmium Selenide

This material can be produced as 1–2  $\mu\text{m}$  thick films in a very inexpensive way using techniques for chemical deposition onto a metal sheet substrate (Kainthla *et al.* 1983). The CdSe forms a Schottky (surface) barrier with an electrolyte such as NaOH. If the electrolyte contains a suitable redox couple such as  $\text{S}/\text{S}^{2-}$  ions produced from dissolved S and  $\text{Na}_2\text{S}$ , the current generated by light incident on the CdSe surface can flow to a counter electrode dipped in the solution, and then via an external load back to the semiconductor. The energy bands and quasi-Fermi levels for electrons and holes (dynamic equilibrium) are shown in Fig. 4 (Haneman and McCann 1982). This is the basis of the photoelectrochemical cell. It has the advantage that no front contact to collect the current need be placed on the film, and that the surface is automatically covered from the atmosphere, although the cell must of course be placed in a (closed) container.

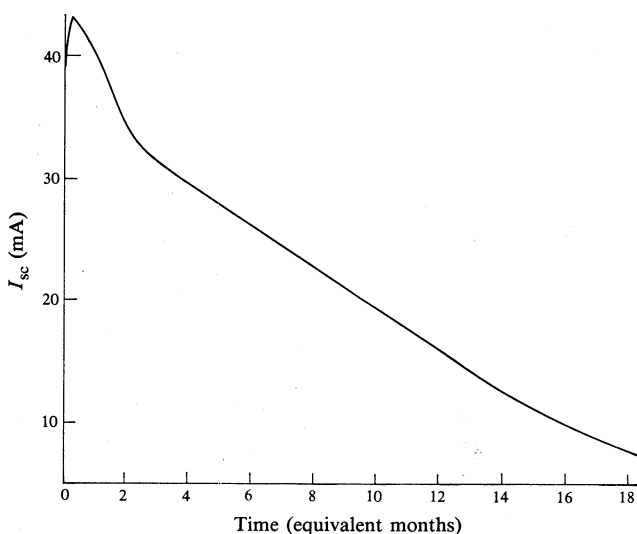


Fig. 5. Decay with time of solar exposure for the short circuit current of a photoelectrochemical cell based on a CdSe photoanode. [From Haneman *et al.* (1984).]

A considerable development program was devoted to this material as a result of its great simplicity of fabrication and its low cost. Efficiencies of 5% were routinely obtained on small (3  $\text{cm}^2$ ) areas and preliminary cells were made up to 90  $\text{cm}^2$ . Reproducible fabrication techniques were developed with batches of cells showing over 90% success rate even with simple laboratory procedures. However, degradation with time of exposure to sunlight occurred. An extensive effort to reduce this effect resulted in considerable improvement, but the lifetime over many months was still not satisfactory, as shown in Fig. 5. The problem was that sulfur ions are discharged at the CdSe surface and the probability of the resultant sulfur atom sticking to the surface is only about 1 in  $10^8$ . Although the effects are negligible in the short term, they build up over the very long exposures of many years needed

in commercial applications. After degradation had occurred, it was found that the films could be restored by heating in air, but it is not certain that this step is commercially viable. Hence, although the system is ideally low in cost in fabrication procedures, the problem of a long lifetime under solar exposure is not yet resolved. A number of other photoelectrochemical systems are under study and techniques for obtaining short term stability for some of them have been developed, but again long term stability remains a problem.

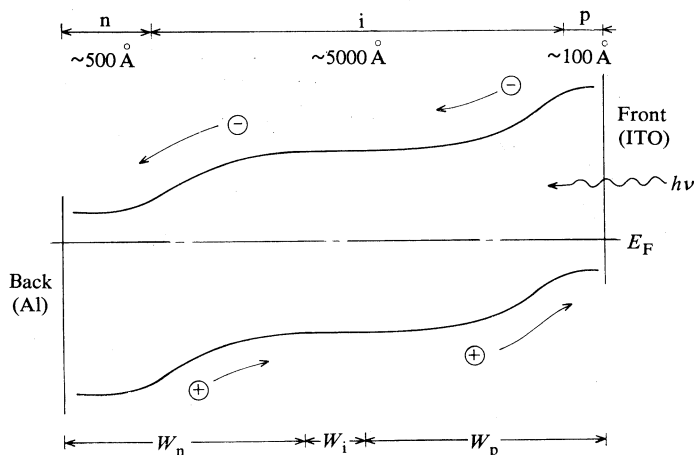


Fig. 6. Variation of energy band edges across a p-i-n a-Si : H solar cell. [From Kennedy and Haneman (1984).]

#### 4. Amorphous Hydrogenated Silicon

In an amorphous material there is no long range order and therefore no restrictions due to crystalline properties on the way light is absorbed (i.e. there is no phonon assistance required near the threshold as in crystalline Si). Hence amorphous Si has a more steeply rising light absorption curve than for crystalline Si (see Fig. 3), so that thinner material may be used. However, many atomic bonds are not engaged (they remain 'dangling'), and these provide sites where fast recombination of excited electrons with the empty hole states can occur, resulting in poor charge-carrier lifetimes. It was found that incorporation of hydrogen atoms into the structure with a concentration of 10–20% saturates the dangling bonds, thus improving transport properties and allowing n- and p-type doping to be carried out on intrinsic (i) material, since the density of unwanted states is now low enough that added impurity states make a difference. There is an approximate energy bandgap arising from the gap between original atomic states, so that with added impurities, p-n junctions can be fabricated and hence various devices such as solar cells. The peak laboratory efficiency obtained for these solar cells is about 10%. A sketch of the energy band structure of a commonly used p-i-n cell is shown in Fig. 6.

Although the films can be produced in various ways, the method currently most used involves a radio frequency discharge in silane ( $\text{SiH}_4$ ) gas, with added  $\text{PH}_3$  (n-type) or  $\text{B}_2\text{H}_6$  (p-type) gases for producing doped layers. The bandgap is about 1.7 eV which is close to the ideal for solar energy conversion (see Fig. 1) and, in addition, is more suited to the spectrum of fluorescent light than crystalline Si (1.1 eV).

Hence amorphous silicon (a-Si:H) cells are more efficient than the crystalline in most office and laboratory locations, leading to their increasing use in powering small calculators and other devices. However, this application does not expose the cells to the continuous strong levels of sunlight and so the serious question of degradation remains to be answered by long term tests. Earlier cells, of about 3% efficiency, appeared to be stable, but later improved cells showing commercial production efficiencies about twice as high appear to suffer some degradation, although it is claimed that the degradation becomes negligible after an initial decay (Hamakawa 1982; Hamakawa *et al.* 1983). This property, along with others, is very sensitive to production procedures, since the manner of deposition of films onto heated substrates in a glow discharge is a complex and not well understood process. There appears to be more than one degradation process, and reduction in minority carrier lifetime has been shown to occur in p-i-n solar cells after prolonged exposure to intensities of AM1. The apparent good stability reported for at least some cells indicates however that technically it will be possible in the future to produce stable solar cells from a-Si:H on a large scale.

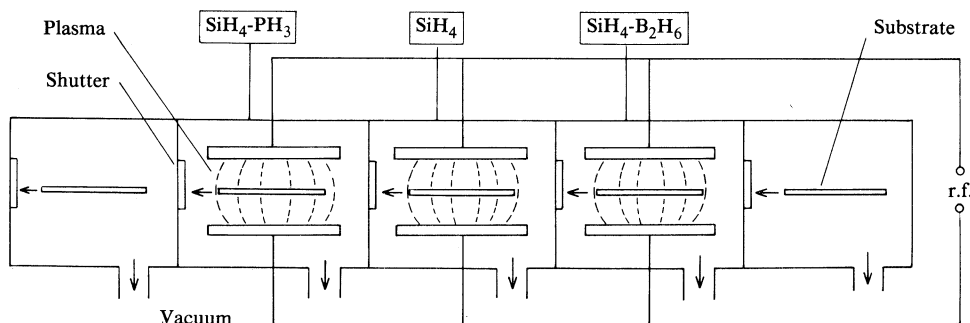


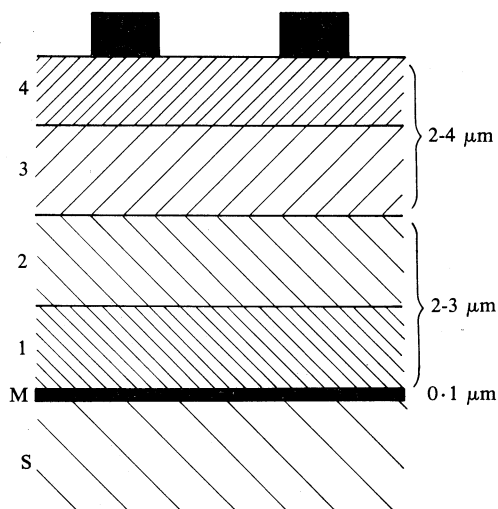
Fig. 7. Consecutive, separated reaction chamber apparatus for the fabrication of a-Si:H solar cells. [Developed by Sanyo (Japan).]

Progress in commercial manufacture of a-Si:H cells is most advanced in Japan, following a large upsurge in research and development activity a few years ago. Both Sanyo and Fuji have been in scale production for several years. A particularly interesting development is the acquisition and further development by Sharp of a continuous production facility developed by Energy Conversion Devices (USA). Here a continuous stainless steel sheet is coated with a 30 cm wide strip of finished n-i-p cells complete with contacts and protective layers. A simplified schematic diagram of a continuous facility (Sanyo) is shown in Fig. 7. Systems such as these appear to be the forerunners of large scale production technology for thin film cells; a single Sharp-ECD machine is capable of producing 3 MW capacity per annum. At present the steel strip is cut into small sections for powering electronic devices, but when the efficiency and stability are sufficiently high it will be marketed for solar power. Precise costs per peak Watt have not been disclosed by major manufacturers, but are known to be already below those of crystalline Si.

As mentioned above, the science of a-Si:H is a complex one. It differs from most thin film systems in that the variation in the properties of the films from different sources is quite considerable, as a result of differences in the quantity of incorporated hydrogen, the degree to which the material is truly amorphous, and the various

incorporations of centres that affect carrier lifetimes and cause long term effects after 'light soaking' (indeed many important centres have not yet been identified). There are also possible columnar growth and porosity properties. Hence, much of the published data, while useful for characterizing the material made by the respective authors, is not necessarily of general applicability. Perhaps a good arbiter of whether a-Si : H from a laboratory is in the small group of 'properly' made (A class) materials is whether it can be used to routinely produce high efficiency devices such as solar cells. This provides some assurance that the mix of properties, including defect centres, approximates that from other laboratories producing such devices. The defect centres can range from hydrogen aggregates, to impurity atoms, or to various bond distortions in the matrix, and clearly an exhaustive study of these is only worth while on reproducible A class material.

The ready ability to introduce other gases into a discharge has been exploited to modify amorphous Si by adding fluorine and also carbon (via methane) into appropriate doped layers so that silicon fluoride and carbide are deposited. Thus a p-layer with amorphous or semicrystalline silicon carbide admixture has a larger bandgap, acting as a more useful window for solar radiation onto the p-i interface. Hence, heterojunctions are formed and the possibilities for these sorts of modifications of amorphous silicon PV devices are considerable; much work can clearly be done in optimizing the structures for specific devices.



**Fig. 8.** Structure of a  $\text{CuInSe}_2$  :  $\text{CdS}$  cell: S is a glass or alumina substrate; M is an Au or Mo back contact; 1 and 2 are low and high resistivity  $\text{CuInSe}_2$  respectively; and 3 and 4 are high and low resistivity  $\text{CdS}$  respectively. [From Mickelsen and Chen (1981).]

## 5. Copper Indium Diselenide Heterojunctions

Another thin film PV system of current interest is a heterojunction between the two thin film semiconductors  $\text{CuInSe}_2$  and  $\text{CdS}$ . Although at first sight it appears complex and costly, progress in the Boeing (USA) laboratory has reached the stage of minor production runs. The significance of the system lies in its demonstrated good stability under prolonged sunlight exposure, making it probably the most stable thin film system currently known. Laboratory cell efficiencies have reached up to about 10% in AM1, using antireflection coatings and graded resistivities inside both components, as shown in Fig. 8.

There are various methods of producing the ternary  $\text{CuInSe}_2$ , but the best results so far have been achieved using coevaporation of the three elements onto a heated substrate (Mickelsen and Chen 1981). This requires careful control of rates of evaporation by using electron impact emission sensors or the less expensive quartz crystal monitors. We have made films with good properties using the latter technique (Szot and Haneman 1984). There is currently considerable research into other techniques of production such as flash evaporation. The costs of the system are not well known for scale production, but once the techniques and control methods have been mastered there appears no reason why deposition onto a continuous heated strip through multiple vacuum chambers should not be possible (see Fig. 7).

The role of (n-type) CdS is to act as a layer transparent to much of the solar spectrum (its bandgap is 2.4 eV), while having a good lattice match (1.2%) and causing a p-n heterojunction with the (p-type)  $\text{CuInSe}_2$ . It is the electric field at this junction which causes the separation of the photo-excited electrons from their holes. The layer must, in addition to good transparency, have good conductivity and this is achieved by just the right amount of indium, incorporated by coevaporation with the CdS.

In practice, heterojunction technology is more complex than single film fabrication. Not only must the individual films have the right properties, but also the critical interface must be properly controlled. This is a growing branch of study of great practical importance, being an extension of semiconductor surface studies. A wide range of measuring techniques are required. Film thicknesses are measured by interference methods where possible, and more generally by gentle mechanical probes which reveal step heights. Composition and structure are characterized by electron microprobe analysis (energy and wavelength dispersive), electron and X-ray diffraction, X-ray photoelectron spectroscopy for surface layers, and Auger electron spectroscopy in conjunction with ion bombardment depth profiling. Electrical transport properties are checked by resistivity and Hall effect measurements, electron and light spot induced current collection with probes, laser-pulse induced time-of-current pulse passage methods and the new method of photovoltage spectroscopy. Optical bandgap and absorption data require spectral scans; information about states in the bandgap comes from optical absorption, deep level transient spectroscopy and related techniques and, where applicable, electron spin resonance measurements. Much information is also obtainable from analysis of the current-voltage curves produced by the structures under illumination.

Some analysis of interfaces can be done by depth profiling but nondestructive techniques mostly rely on the interpretation of electrical behaviour. This requires a good knowledge of the theory of current flow through heterojunctions, and it is only recently that theories without too many simplifying assumptions have been extended to cope with the complexities (Hinckley *et al.* 1984). The problem with most interfaces is how to produce them as free as possible from carrier traps and recombination centres, and this requires not only good lattice matching but the technology of producing the upper film without contamination and damage to the lower.

## 6. Conclusions

As is evident from Table 4, a large variety of film systems are under active study but full information on their durability, reproducibility and cost is harder to obtain

than figures such as peak laboratory efficiency. The significance of the latter can only be assessed in conjunction with the former. This explains why heavily touted and funded systems such as the silicon ball hydrogen bromide project of Texas Instruments ceased rather abruptly. Also, methods of stabilizing films such as ruthenium treatment of GaAs may be effective in the short but not in the long term.

At this stage we cannot go into detail on the other systems given in Table 4 since all the significant data have not been made available. Their potential is not easy to judge since the pace of development is appreciable. In particular, the general performance possibilities of ternary semiconductor compounds and heterojunctions with suitable binary or ternary window materials are very great. Even in a-Si:H, the ready ease of incorporating other gases into the discharge and thereby fabricating heterostructures has only been taken advantage of fairly recently. Furthermore, it has long been realized that the waste of the solar spectrum as a result of using only a single semiconductor receiver can be reduced by using multiple or stacked cells of different semiconductor bandgaps. The practical realization of such structures is coming closer. Hence the whole field of semiconductor film technology lends itself to development of new and ingenious combinations, and the necessary expertise and techniques are evolving to meet the goals. While photovoltaic applications are clearly a leading target, many other possibilities for electronic and optoelectronic devices are being explored and the future holds much promise.

## References

- Chopra, K. L., and Das, S. R. (1983). 'Thin Film Solar Cells' (Plenum: New York).
- Hamakawa, Y. (1982). *Sol. Energy Mat.* **8**, 101.
- Hamakawa, Y., Fujimoto, K., Okuda, K., Kashima, Y., Nonomura, S., and Okamoto, H. (1983). *Appl. Phys. Lett.* **43**, 644.
- Haneman, D., and McCann, J. F. (1982). *Phys. Rev. B* **25**, 1241.
- Haneman, D., Wantenaar, G. H. J., and Kainthla, R. C. (1984). *Sol. Energy Mat.* **10**, 69.
- Hermann, A. M., Fabick, L., Zweibel, K., and Hardy, R. (1982). Proc. 16th IEEE Photovoltaic Specialists Conf., p. 840 (IEEE: New York).
- Hinckley, S., McCann, J. F., and Haneman, D. (1984). A flux analysis of multiple junction solar cells. *J. Appl. Phys.* (in press).
- Kainthla, R. C., McCann, J. F., and Haneman, D. (1983). *Sol. Energy Mat.* **7**, 491.
- Kennedy, D. F., and Haneman, D. (1984). *J. Appl. Phys.* **55**, 1168.
- Lehner, G. (1983). Proc. Solar World Congress, Perth 1983, Extended Abstracts (Ed. S. V. Szokolay), p. 308 (ISES: Perth).
- Matsumoto, H., Kuribayashi, K., Uda, H., Komatsu, Y., Nakano, A., and Ikegami, S. (1984). *Sol. Cells* **11**, 367.
- Mickelsen, R. A., and Chen, W. S. (1981). Proc. 15th IEEE Photovoltaic Specialists Conf., San Diego, p. 800 (IEEE: New York).
- Szot, J., and Haneman, D. (1984). Preparation and characterization of CuInSe<sub>2</sub> and CdS films. *Sol. Energy Mat.* (in press).
- Wysocki, J. J., and Rappaport, P. (1960). *J. Appl. Phys.* **31**, 571.