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"Solar Energy Applications of Thin Films"

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SOLAR ENERGY APPLICATIONS OF THIN FILMS

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1. Introduction :

Energy is undoubtedly the life line for development of any nation. The direct relationship between the per capita income with the energy consumed is well established. Fossil fuels, namely coal, oil and gas, have been the work horse of conventional energy sources for most of the world. But the rapid depletion of these sources have led mankind to experiment with renewable sources of energy such as wind, hydro, geo, bio and solar. These sources are, of course, generated directly or indirectly by the sun. The sun is a safe and well maintained gigantic nuclear reactor located millions of miles from the earth. Its radiates to earth 10,000 times more energy than the total world requirement today. Besides being abundant, it is free and is free of pollution and geographical and political constraints. Nevertheless, it is a low grade and low density energy source which requires special materials with large surface areas to convert it into a useful form of energy.

The solar energy may be converted directly to heat (called solar thermal), electricity (solar photovoltaic), chemical reactions (photochemical) electrochemical reactions (photo electrochemical) and photosynthesis (biomass). Since the total energy is directly proportional to the area, all solar energy devices have to be necessarily large in surface area in order to produce significant energy for applications. Thus, it is essential to use as thin and as readily available and cheap material as possible with as high an optical absorption coefficient as possible so that the energy conversion becomes economically viable. Consequently, thick and thin films and associated technologies for large scale production are expected to play a dominant role in solar energy conversion.

What are Solar Cells ?

The phenomenon of conversion of light directly into electrical energy is called Photovoltaics (PV), or Solar Photovoltaics (SPV) in case the light is from the sun. The conversion device is called Photovoltaic cell or Solar Cell. A basic solar cell consists of two materials of different electron densities brought together to form a junction. Transfer of electrons across the junction leading to a gradient of charges sets up an electrostatic potential at the junction which opposes further flow of charges so that an equilibrium is created. If one material has excess electrons (n-type) and the other excess holes which means deficit in electrons (p-type), it is called a p-n junction. One may insert an intrinsic (i) material having roughly equal number electrons and holes, or a suitable insulator (I), between p and n to form p-i-n junction. Depending on the type of inhomogeneity, solar cells may be classified as p-n homojunctions (same material), p-n heterojunction (two different materials), p-i-n, metal-semiconductor Schottky barrier, metal-insulator-semiconductor (MIS) cell, metal (1) - insulator-metal (2) cell, semiconductor-electrolyte (PEC) cell etc.

Physics of Solar Cells

The basic aim in photovoltaic conversion is to create electron-hole pairs by absorption of the solar spectrum in a material (usually a semiconductor), collection of these carriers and conversion and separation of these carriers into majority carriers and, finally, distribution into an external load.

The semiconductor absorbs the solar radiation and generates electron-hole pairs according to

$$G(x) = \int_{Eg}^{\infty} N(E)\,[[1 - R(E)]\,\alpha(E)\exp[-\alpha(E)\,x]]\,dE$$

where G(x) is the generated number of pairs at any point x (with the origin at the surface through which light enters), E_g is the bandgap of the semiconductor, N is the photon flux at energy E, R(E) is the reflectance at energy E and α (E) is the absorption coefficient at energy E. Separation of the charge carriers and conversion into majority carriers take place at a surface where a field exists. This surface is usually the interface of the junction(s) of the dissimilar materials.

The fraction of G(x) that reaches the field region at the interface is determined by the diffusion length of the carriers and, therefore, the lifetime. Both the lifetime and diffusion length are related to the mobility of the carriers by the Einstein relation [$L_D = (D\tau)^{1/2} = (\mu kT\,\tau/q)^{1/2}$]. Depending, on the scattering process, the mobility can be dominated by grain boundary processes or by impurity scattering processes. In general, small grain sizes and high impurity concentrations lead to a smaller mobility and, consequently, small diffusion lengths and low minority lifetimes.

Once the carriers reach the filed region, they are collected and separated across the barrier. The number of carriers which cross the junction without recombining depends on the field magnitude and distribution at the junction which, in turn, are determined by the potential distribution at the junction. The diffusion voltage at the junction is the difference in work function of the two materials constituting the junction ($\phi_p - \phi_n$, where ϕ is measured from the Fermi level to the vacuum level). The potential distribution and the spatial distance over which the diffusion voltage extends are dependent on the doping level, the doping profile and the dielectric constant of the materials. Obviously, the higher Hu diffusion voltage and, hence, the higher field result from larger work function separation. In the case of a homojunction, this implies a larger bandgap and higher doping density. This requirement is in direct conflict with the requirement of a low bandgap and lower doping for higher carrier generation and collection. Thus, for optimum performance, a delicate balance between various material properties has to be achieved. The calculated maximum efficiency for homojunctions and heterojunctions as a function of bandgap expectedly exhibits a broad maximum less than of 30% in the bandgap range 1.1 -1.4 eV.

2. Optimization of Solar Cell Parameters

In order that a substantial fraction of the generated carriers reach the junction, the carriers must be generated within a distance of the order of the diffusion length from the junction. This requirement imposes a dual condition on the material properties, viz. a high absorption coefficient and, consequently, low absorption thicknesses and a long diffusion

length. Alternatively, a drift field can be provided in the bulk of the absorber which increases the effective diffusion length of the carriers. The drift field can be obtained either by a spatial gradient in the impurity concentration profile or by a spatially varying bandgap in a gradient composition material. The effective diffusion length can be enhanced considerably by providing a gap gradient, as demonstrated for a graded bandgap Cd $Hg_{1-x}Te$. It should be noted that at the surface of a semiconductor a large density of surface states exist. This leads to a large surface recombination velocity and the carriers generated near the free surface diffuse towards this surface and are lost via surface recombination. A counteracting field (called a back surface field or a minority carrier reflecting field) at this surface helps to direct the minority carriers away from the surface and towards the collecting junction. Such a surface field is achieved by changing the doping profile at the surface (a high / low junction) as in the case of Si and $CuInSe_2$/CdS solar cells or by providing a heteroface junction at the surface as in GaAlAs/p-GaAs/n-GaAs and Cu_2O/Cu_2S/CdS solar cells. In both cases, multilayer structures are necessary.

From the preceding discussion, it is clear that the number of carriers collected depends on the following factors : E_g, N, Φ, α, L_D, R, d, F_d, F and S where R is the grain size, d is the thickness of the absorber layer, F_d is the drift field, F is the field at the junction and S is the surface recombination velocity.

The current-voltage (I-V) relationship of a photovoltaic device, in general, follows the equation

$$I(V) = I_{si} [\exp (qV/n_1kT)^{-1}]-I_L$$

where I_s is the reverse saturation current, I_L is the photocurrent and n is the diode factor. The value and form of Is depends on the particular transport mechanism that dominates at the junction, viz. bulk recombination and emission or diffusion over a barrier, generation-recombination in the depletion width, interface recombination, Schottky emission or tunnelling. Different mechanisms can dominate under different conditions of bias and / or illumination. Most practical devices exhibit a combination of these processes and hence the summation over all the mechanisms is necessary. The diode factor takes the value 1 for emission and diffusion mechanisms and the value 2 for generation-recombination mechanisms.

The various photovoltaic parameters of interest are : (i) the open-circuit voltage (V_{oc}), which is the voltage for zero current flow, (ii) short-circuit current (I_{sc}), which is the current (iii) the maximum power point P_m, where the product of I x V is maximum and corresponds to the operating point; (iv) the fill factor (FF) defined as $V_mI_m/V_{oc}I_{sc}$, where V_m and I_m are the voltage and current values at P_m, and (v) the efficiency (η) defined as $V_mI_m/P(input) = V_{oc}.I_{sc}.FF/P_{in}$. The V_{oc} has the form

$$V_{oc} = nkT/q \ln (I_L / I_s)$$

For high V_{oc} and also for high efficiency cells, I_s should be low. I_s is lowest for the bulk recombination case for which n = 1. The existence of grain boundaries provides recombination surfaces, decreasing lifetimes and increasing I_s. Also deep level impurities reduce the bulk lifetime. In heterojunctions, if the lattice parameters of the two materials are not well matched, a large density of states occur at the interface providing a path for the recombination of carriers during their traversal across the junction.

Moreover, if the electron affinities are not matched, either a notch or a spike or a discontinuity could be present at the conduction band edge. The notch or spike would impede the flow of carriers across the junction while the discontinuity would help in carrier recombination at the interface states. Thus, in a heterojunction, proper lattice parameters and electron affinity matching is essential. It should be noted that the efficiency of a heterojunction device is always lower than the efficiency of a homojunction device fabricated from the lower gap material. In a CIS type device, for optimum operation, the band at the junction should be strongly inverted and the insulator layer should be thin enough so as to be transparent to the electrons crossing over from the semiconductor to the metal. The work function of the metal / electron affinity of the semiconductor has to be properly chosen so as to obtain conditions of inversion at the interface. The thickness of the insulator layer, its coherence and integrity and the surface states critically determine the performance of the device. In PEC cells, the electrolyte potential and the optical absorption in the electrolyte sensitively influence the I-V characteristics and efficiency of the cell.

The stringent requirements of lattice matching and electron affinity matching in heterojunction devices restrict the photovoltaically useful material combinations to such cells as CdS/InP, CdS/$CuInSe_2$, Cu_2S/CdZnS and CdTe/CdZnS, etc. To utilise more semiconductor materials, it is necessary to synthesis ternary, quaternary, and quinary alloys with tailored bandgaps, lattice parameters and electron affinities.

3. Tailor-Made Junctions

Even under the best conditions of no reflection loss, unity quantum efficiency (number of electron-hole pairs generated per photon absorbed), zero recombination loss and unity collection at the interface, the highest efficiencies for photovoltaic devices at the optimum bandgap are in the range of 23 to 27% (depending upon the assumptions). Over 60% of the incoming incident energy is lost in either photon losses (no absorption at energies below bandgap), or in incomplete utilisation of the incident power. The latter occurs due to free carrier absorption, which does not contribute to pair generation and due to the photon energy in excess of the bandgap being dissipated as heat by thermalisation of the generated carriers. Thus only a fraction of the solar energy is utilized in producing electrical energy for a homojunction of bandgap Eg.

A heterojunction utilises the solar spectrum more efficiently, resulting from a better match due to the two bandgaps. A series of semiconducting materials with successively increasing bandgaps would obviously provide a perfect absorption characteristic match with the solar spectrum. This concept of dividing the solar spectrum and utilizing each portion to portion to provide input power to individual solar cells with spectral response and bandgap matched to that region of the spectrum has led to the design and analysis of the high efficiency cascade cells with very low power losses and conversion efficiencies in the range of 30 to 70%.

Cascade operation can be achieved in two ways. In an optical filter-mirror-concentrator-cells system, the solar spectrum is made incident on a interference filter-mirror via a concentrator lens. The filter-mirror has complementary reflectance and transmittance characteristics. The reflected spectrum is incident on a cell with a spectral response and, hence, a bandgap matched to the reflected spectrum while the transmitted spectrum is incident on another cell with spectral response and bandgap matched to the transmitted spectrum. The

scheme can be extended to include three or more cells to obtain a closer fit to the solar spectrum. The reflectance and transmittance spectral characteristics play a critical role in achieving high efficiencies and such spectral characteristics are possible only by using multilayer interference stacks.

In another arrangement, two or more cells are placed one behind another, with the cell with the highest bandgap facing the incident radiation, the cell with the next highest bandgap being placed second and so on to the cell with the lowest bandgap which is placed at the end. Each successive cell utilises a portion of the transmitted incident spectrum, corresponding to its spectral response and bandgap. In this manner, spectrum splitting is effected without the use of optical filter-mirrors. Using a large number of cells with bandgaps separated by small amounts, an almost perfect match with the solar spectrum can, in principle, be achieved. This arrangement is called the tandem junction solar cells. The cells can be connected in series to obtain a high Voc. However, for high efficiency operation it is imperative that the cells should be matched, i.e. the same photocurrent should flow through all the cells as otherwise power losses would occur. Since it is not possible to match individual solar cells fabricated from available semiconductor materials it is necessary to synthesize semiconductor materials with tailored bandgaps. Simultaneous electron affinity and lattice matching requires the use of alloy semiconductors, usually ternary, quaternary and quinary systems in order to achieve the desired structural and electronic characteristics. In a more sophisticated version, the cells can be internally series connected in an integrated tandem (IISC) structure. The two cells are internally connected by a tunnel junction. IISC devices for various material combination and device structures have been analysed and efficiencies as high as 72% have been predicted for a 36 cells combination.

The desirable features for high performance are : **(1)** the absorber layer should possess a bandgap in the region of 1-2 eV preferably around 1-5 eV, **(2)** a high absorption coefficient greater than $10^4 cm^{-1}$, **(3)** a large minority carrier diffusion length $\sim$ several microns, low density of recombination centres and low surface recombination velocity < 104 cm/se, **(4)** in the case of polycrystalline material, the grains should be large. Further, neutralisation or passivation of the grain boundaries is essential; **(5)** for heterojunctions, electron affinity and lattice parameter matching are necessary for obtaining high V_{oc}; **(6)** drift fields in the absorber material need to be incorporated either by gradient doping or by gradient bandgap (particularly when the minority carrier diffusion length is low), and finally **(7)** for cascade operation, devices have to be fabricated with spectral response and bandgap matched to a particular portion of the solar spectrum. Further, if the cells are series connected either internally or externally, the individual photocurrents have to be matched to avoid power losses. This imposes stringent material requirements and perfect tailoring of bandgaps, lattice parameters, electron affinities and device geometries.

4. Why Thin Films ?

It is clear from the preceding discussion that the requirements for high performance cells can be met only by tailored materials which is feasible only in the form of thin films due to the basic processes governing the ab-initio creation of thin films. Some of the salient points supporting this conclusion are :

- High α, Low L and High S Solar Cell Material must be in Thin Film Form for Optimum Efficiency
- Material Economy
- Large Areas & Desired Shapes
- Choice of Various Simple and Sophisticated Deposition Techniques Available
- A Variety of Microstructures & Crystal-structures - (Amorphous, Polycrystalline, Oriented, Epitaxial) Available
- Topography Ranging from Very Rough to Atomically Smooth - Controlled Texturization Possible
- Different Types of Junctions - Homo, Hetero, Scmottry, Pec, Etc. Possible
- Multi Junctions Feasible
- Tandem Junctions & Multi Terminal Junctions Possible
- Cell Integration Easily Achieved to Form Modules
- Compatibility with Solar Thermal Application
- Tailorability of
  - Composition of Alloys / Compounds
  - Graded Compositions
  - Microstructure
  - Exotic Materials
  - Lattice Constants
  - Band Gap
  - Electron Affinity
  - Junction Position and its Electronic Profile
  - Design Parameters
- Pv Economics - Only Viable System for < 1$/w at Large Production Level

Thin Film Materials

Historically, the Photovoltaic action was first discovered in Se and Cu_2O. The latter was a thin film Schottky barrier exhibiting about 2% efficiency. Later, the discovery of solar cell action in CdS/Cu_2S heterojunction led to extensive R/D work on the first completely thin film solar cell based on this junction. The well-known Clevite process and its variations were used for commercial production of this cell in US and France. After intensive work (which laid the foundation of the Physics of Thin Film Solar Cells) cell efficiencies above 12%, and module efficiencies $\sim$ 6% were obtained. However, despite being an ideal cell from Physics point of view, its life due to metallurgical and chemical degradation of the junction interface remained problematic. With more attractive materials on the horizon, and in particular, the rapid growth of crystalline and amorphous silicon technologies, the whole world-wide effort on this cell came to a sad end.

Silicon is the only elemental material of interest for PV. Only recently, n and p doped films of diamond-like carbon and fullerence have been obtained and efficiencies $\sim$ 2% have been achieved. The number of possible PV materials increases rapidly as we consider suitable alloys / compounds of binaries, ternaries and tertiaries. Although a large number of such thin film materials have been reported in literature, the choice of viable PV materials for very detailed work has been limited to a few so far. This list includes : crystalline(-c)Si;

hydrogenated amorphous silicon (a-Si:H); CdTe; GaAs; $CuInSl_2$ and CuInS. A brief status review of these materials in given in the following section.

1. Crystalline Silicon

Because of considerable knowledge available on silicon and its processing for the microelectronic chip technology, commercial efforts on solar cells have focussed on single crystal and multicrystalline silicon wafers. As a result, research on silicon films has remained at a very low pace. Only recently when it has been realized that the cost of production of silicon solar cells cannot be brought down below \$4/Watt, due to the cost of the materials and the energy intensive unit processes, the research on silicon films has started seriously.

Epitaxial and polycrystalline (grain size $\sim$ few μm) films of silicon have been deposited by e-beam, sputtering, CVD, and PECVD techniques. Various innovations out as taxturization, back surface field and grain boundary passivation have been tried. The progress is achieving good performance has been good. It is too early to project costs for a large scale production plant primarily because the production process has not yet been finalized.

Some highlights of both single crystal and thin film polycrystalline silicon cells are given below :

- Efficiency of single crystal Si cells (Laboratory) has been rising steadily upto $\sim$ 24% as a result of better understanding of the junction properties and innovations in cell design and fabrication technologies.
- Efficiency gap between best laboratory cells, submodules / modules, and mass produced modules varies with the maturity of technology and can be at least 10% at every step so that the manufactured cell may be as low as 50% of the efficiency of the best laboratory cell.
- The world PV production of $\sim$ 125 MW in FY 1997 is primarily ($\sim$ 85%) based on single, crystal and polycrystalline silicon. At the present rate of growth, it is expected to touch 200 MW/Year figure in FY 2000.
- With increasing production of Si-PV from 200 kW in 1976 to 125 MW in 1997, the cost of solar cells has decreased from \$100 to about \$4/Wp (FY 1998).
- With the existing technology and the material cost, the cost of Si cells can not be decreased significantly unless major innovations in the production of appropriate quality silicon in thin sheets take place.
- Present day technology uses 6" pseudo square of $\sim$ 300 μm thickness, with an efficiency of $\sim$ 14-15%. The energy (16-5 kWh/Wp) pay back period of such cells is $\sim$ 3-4 years.
- Specially designed silicon solar cells with efficiency $\sim$ 18% are being manufactured on a limited scale for special applications (e.g. for concentration).
- Polycrystalline silicon solar cells with efficiency $\sim$ 12-14% are being produced on MW scale.
- Specially designed thin ($\sim$ 20 μm) films silicon solar cells with efficiency $\sim$ 12% have been fabricated on a lab scale.
- Single crystal silicon cells are expected to have a working life > 25 years.

- Efficiency of useful size modules of silicon cells is ~ 12%.
- The cost of a SPV system including power conditioning equipment and batteries is ~ $10/Wp (FY 1998).
- Cost of SPV based on crystalline silicon can be lowered only by such innovations as :
  - Production of silicon and cells at a scale of > 100 MW
  - Production of silicon in the form of thin (< 100 μm) sheets of single / multicrystalline silicon
  - Large area thin films of silicon of appropriate quality
  - Low cost substrate
  - Passivation of defects and surfaces
  - Cheaper contact materials
  - Cheaper packaging materials and processes
  - Cell design innovations (e.g. Burried contacts; Photon Trapping, etc.)

2. Amorphous Silicon (a-Si-H)

The discovery of the possibility of doping a-Si films after hydrogenation led to phenomenal growth of science and technology of a-Si:H films. The possibility of manufacturing cheap large area solar cells was the main driving force. Consequently, a number of cell manufacturing facilities based on glow-discharge deposited a-Si:H films were established throughout the world. At one time, commercially produced a-Si:H solar cells contributed almost 40% of the world PV production.

A typical flow chart of an automated manufacturing line is shown in Fig. 1. Also shown is how the cells are connected in series.

Figure 2 shows the structure of a single junction cell and a multijunction cell.

Out of the must serious problems with a-Si:H cells is the inherent degradation due to the Staebler-Wronski effect. Accordingly, the conductivity of the film increases on illumination and thin decreases in dark. Cycling with illumination produces some irreversible changes which are still not properly understood but are definitely due to structural changes in the dangling bonds and rearrangement of bonded hydrogen. The effect can be reduced either by having thinner absorption layers, or by reducing the internal field, or by suitable alloying agents. All these concepts have been tried out. As a result, rather complex structures such as stable and triple junction cells tandem and cascade cells have emerged as seen in Fig. 2.

A summary of the significant points related to a-Si:H cells is given in the following.

- a-Si-H PV technology has lost ground from ~ 39% world PV share in 1988 down to ~ 10% in 1997.
- The glow discharge technology is well established production tool.
- The highest efficiency obtained in the lab cells is ~ 16%.

- Single junction cells degrade down to $\sim$ 5-7% efficiency over a period dependent on how these are used.
- Numerous innovations such as cell integration, graded gap, multi-junctions, light trapping have contributed to the improvements in the cell performance.
- Stability has been improved with double and triple layer cells. 5 and 10 MW plants for triple layer cells have been set up recently. The best stabilized (claimed!) module efficiency is $\sim$ 7%.
- The present day cost of a-Si:H cells and modules is comparable to that of single crystal silicon.
- Because of the lower throughput, complex deposition technology for triple junction cells, and material cost, the cost can be brought down only with much larger (> 10 MW) scale production, or with breakthroughs which help stabilize simpler single junction cells.
- Major applications of a-Si-H cells are for small scale, small power, value added electronics.
- The energy payback time for 3% stable efficiency cells and a 10 MW plant is $\sim$ 1 year.
- Large scale revival of the a-Si-H technology is doubtful. Major module producers today are : Sanyo, APS, USSC, PST, NAPS, Fuji, Solarex, etc.

3. Ga As

From the point of view of optimum optical gap, high absorption coefficient and high quantum efficiency, GaAs is ideally suited for high efficiency solar cells. Among other features are :

- Deposition techniques include MBE, MOCVD, CVD and LPE
- Homo, Hetero, Stacked Multijunctions, Tandem Junction and PEC possible
- Efficiencies : Homo (23.3%), AlGaAs/Si (26.9%), AlGaAs/GaSb Tandem (32.6%), GaAs/InGaP (30%), Stacked InGaAs and InGaP (33%)
- Junction formation straightforward
- Various types of junctions possible
- Suitable for stacked cell application
- Stable Cell. Good for high temperature applications
- Expensive materials and processing
- Limited Laboratory batch size production for specialized applications

Several deposition technique have been utilized to prepare excellent quality expitexial films and high efficiency solar cells have been fabricated. However, the material and processing techniques being expensive, the GaAs cell is expected to be useful for specialized applications in space, defines and sophisticated electronic equipment where power to weight ratio is critical.

4. CdTe

Figures 3 shows the structure of the optimized high efficiency CdTe cell. The fabrication steps and the process flow sheet are shown in Figs. 4 and 5, respectively.

A summary of the significant features of CdTe cell are given in the following :

- Theoretical Efficiency : $\sim$ 30%
- Deposition Techniques :
  - CdTe by Evaporation / Sublimation / Chemical Solution / Screen Printing
  - CdS by Evaporation / Sublimation / Chemical Solution
- Lab Cell Efficiency Achieved : $\sim$ 15%
- Module Efficiency : $\sim$ 8%
- Production Plants :
  - Matsushita; Golden Photon; Solar Cell Inc; BP Solar; Polyplex .... $\sim$ 1 MW Plants planned but not functional
- Nature of Junction : Controversial
- Formation of Good Junction : Empirical requiring Suitable Heat, Chemical and $CdCl_2$ Treatment required
- Estimated Cost : $\sim$ 1$/Wp for 10 MW plant
- Pay Back Time : 1.6 months for 10 MW plant
- Stability : Good
- Problems : Cd Toxicity and Te Availability
- Production Technology : Not mature due to temperamental junction

Unless some critical problems such as contacts and junction formation mentioned above an resolved, large scale production of CdTe based cells is not likely despite good intentions of several major manufacturers in the field.

5. Cu-In (Ga)-Se(S) Based Cell

Despite its lower band gap, this generic material has some ideal properties for solar cells. The structure of the solar cell and its process flow sheet are given in Fig. 6 and 7.

The significant features of thin generic cell are given in the following :

- Theoretical Efficiency : $\sim$ 28-30%
- Deposition Techniques :
  - Co-evaporation and homogenization
  - Layered vacuum deposition followed by selenization with Se or H_2Se
  - Sputter deposition followed by selenization
  - Spray deposition
  - Screen printing followed by selenization

- Lab Cell Efficiency Achieved : ~ 18%
- Module Efficiency : ~ 11%
- Production Plants (by Siemens Solar; ISET; EPV) ~ 10 MW Planned; Presently kilowatts only
- Estimated Cost : ~ 1$/Wp at > 10 MW Production
- Pay Back Time : ~ 4 months for 10 μm plant
- Stability : Good
- Problems :
  - Multiple Binary Phases; Polymorphism; Structural and Electronic Disorder
  - Availability of In and Ga
- Production Technology :
  - Sensitive Structure;
  - Sophisticated Controls Required
  - Upscaling Problematic

Several manufacturers are preparing to commercialize the cell. However, unless some processing steps (such as selenization and deposition of alloy films) are simplified for production, this cell will remain in the R/D stage.

Comparative Analysis

A comparative analysis of the efficiencies of various thin-film cells mentioned above is given in Table I. Also given in Table II are the best cell and module efficiencies attained so far.

Confirmed cell and submodule efficiencies under AM1.5 spectrum (1000 W m^{-2}) at 25 °C

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA cm^2)	FF (%)	Test centre (and date)	Source
Si (crystalline)	24.0	4.0 (ap)	0.709	40.9	82.7	Sandia (9/94)	UNSW PERL
Si (multicrystalline)	18.6 ± 0.6	1.0 (ap)	0.636	36.5	80.4	NREL (12/95)	Georgia Tech HEM
Si (supported film)	16.6 ± 0.5	0.98 (ap)	0.608	33.5	81.5	NREL (3/97)	AstroPower (Si-Film)
Si (crystalline)	22.7	778 (da)	5.60	3.93	80.3	Sandia (9/96)	UNSW/Gochermann
Si (multicrystalline)	15.3	1017 (ap)	14.6	1.36	78.6	Sandia (10/94)	Sandia/HEM
GaAs (crystalline)	25.1 ± 0.8	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin, A/GaAs window
GaAs (thin film)	23.3 ± 0.7	4.00 (ap)	1.041	27.6	83.8	NREL (4/90)	Kopin, 5-μm CLEFT
GaAs (multicrystalline)	18.2 ± 0.5	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI, Ge substrate
InP (crystalline)	21.9 ± 0.7	4.02 (t)	0.878	29.3	85.4	NREL (4/90)	Spire, epitaxial
CdTe (cell)	16.0 ± 0.2	1.0 (ap)	0.840	26.1	73.1	JQA (3/97)	Matsushita, 3.5-μm CSS
CdTe (submodule)	10.6 ± 0.3	63.8 (ap)	6.565	2.26	71.4	NREL (2/95)	ANTEC
CdTe	9.2 ± 0.5	3366 (ap)	45.59	1.10	62.1	NREL (4/97)	Golden Photon
CIGS (cell)	16.4 ± 0.5	1.025 (t)	0.678	32.0	75.8	NREL (11/94)	NREL, CIGS on glass
CIGS (submodule)	14.2 ± 0.2	51.7 (ap)	6.808	3.1	68.3	JQA (10/96)	Showa Shell
CIGSS	11.1 ± 0.6	3665 (ap)	26.01	2.32	57.4	NREL (4/97)	Siemens Solar
a-Si (cell)	12.7 ± 0.4	1.0 (da)	0.887	19.4	74.1	JQA (4/92)	Sanyo
a-Si (submodule)	12.0 ± 0.4	100 (ap)	12.5	1.3	73.5	JQA (12/92)	Sanyo
Nanocrystalline dye	*6.5 ± 0.3*	*1.6 (ap)*	*0.769*	*13.4*	*63.0*	*FhG-ISE (1/97)*	*INAP*
GaInP/GaAs	30.3	4.0(t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic)
GaAs/CIS (thin film)	25.8 ± 1.3	4.00 (t)	- -	- -	- -	NREL (11/89)	Kopin Boeing (4-terminal)
a-Si/CIGS (thin film)	14.6 ± 0.7	2.40 (ap)	- -	- -	- -	NREL (6/88)	ARCO (4-terminal)
a-Si/a-Si/a-SiGe	13.5 ± 0.7	0.27 (da)	2.375	7.72	74.4	NREL (10/96)	USSC (monolithic)
a-Si/a-SiGe/a-SiGe (tandem)	10.2 ± 0.5	903 (ap)	2.32	6.47	61.2	NREL (12/93)	USSC

* (ap) = aperture area; * (t) = total area; * (da) = designated illumination area;

TABLE II

Material	Best Cell η (%) (Approx.)	Production Module η (%)	Life Stability	Production Technology	Production (1998)	Cost ($/Watt)	Remarks
• C-Si (Sc / poly)	~ 23	12 - 15 (18% special)	> 20 yrs. Excellent	Proven & Mature	~ 125 MW	4	Reliable but expensive
• C-Si (Sheets / Films)	~ 12	~ 10 (Pilot)	Long Good	UD (Under Development)	?	?	Very Promising
• a-Si:H	~ 15	7 (Triple Jct)	Variable	Proven	~ 30 MW	4	Viability Questionable
• Cd Te	~ 15	7 (Pilot)	? Good	UD	~ kW	< 1	ONLY simple and cheap production process would make it VIABLE
• Cu-In-Se	~ 18	11 (Pilot)	Long Good	UD	~ kW	< 1	- do -
• GaAs	~	(Pilot)	Long Good	Conventional Microelectronics	~ kW	?	Good for specialized space applications

CONCLUDING REMARKS

- EFFECTIVE UTILIZATION OF THIN-FILM TECHNOLOGIES, THIN-FILM CONCEPTS AND NOVEL CELL DESIGNS HAVE LED TO STEADY AND IMPRESSIVE PROGRESS IN IMPROVING THE EFFICIENCY OF A NUMBER OF LARGE AREA POLYCRYSTALLINE THIN FILM SOLAR CELLS BEYOND 10%.

- THE $\sim$ 16% CELL AND 10.1% MODULE EFFICIENCY FOR CdTe CELL; $\sim$ 18% CELL AND 11.1% MODULE EFFICIENCY FOR CIS CELL; 15.7% CELL AND 10.9% MODULE EFFICIENCY FOR SILICON FILM CELL ARE INDEED VERY SIGNIFICANT ACHIEVEMENTS.

- MONOLITHIC INTEGRATION TECHNIQUES ARE NOW STANDARDIZED.

- WITH FURTHER INNOVATIONS IN DESIGN, USE OF PHOTON TRAPPING, SURFACE AND GB PASSIVATION, AND CONTROL OVER THE PROPERTIES OF INTERFACES (WITH TCO AND CdS), CdTe AND CIS BASED CELLS ARE EXPECTED TO TOUCH $\sim$ 20% EFFICIENCY.

- DESPITE INCOMPATABILITY OF DEPOSITION TECHNIQUES FOR CdTe AND CdS AND THE "EMPIRICALLY" EVOLVED JUNCTION, CdTe CELL IS "MANUFACTURABLE" THE CELL STABILITY DEPENDS ON INTERFACIAL INTERACTIONS AND QUALITY OF ENCAPSULATION AGAINST WATER VAPOURS.

- COMPLEX SYNTHESIS TECHNIQUES FOR CIS AND THE RANGE OF STRUCTURAL, CHEMICAL AND ELECTRONIC DISORDER INHERENT IN SUCH A MULTINARY MAKE "MANUFACTURABILITY" A QUESTION MARK AT PRESENT. BUT, A VIABLE SOLUTION MAY YET EMERGE THROUGH THICK FILM TECHNOLOGY.

- ALTHOUGH THE EMERGENCE OF A CLEAR FRONT RUNNER CELL AND THE ASSOCIATED TECHNOLOGY (IES) HAS NOT YET TAKEN PLACE, IT IS CLEAR THAT SINGLE ELEMENT POLYCRYSTALLINE FILM / SHEET SILICON CELLS WILL BE THE MOST PREFERRED IN VIEW OF THE VERY WELL ESTABLISHED SILICON TECHNOLOGY.

- THIN FILM SOLAR CELLS BASED ON NEW AND TAILORED MATERIAL WILL CONTINUE TO CHALLENGE INNOVATIVE R/D FOR SOME YEARS BEFORE COST EFFECTIVE LARGE SCALE PRODUCTION BECOMES A REALITY.

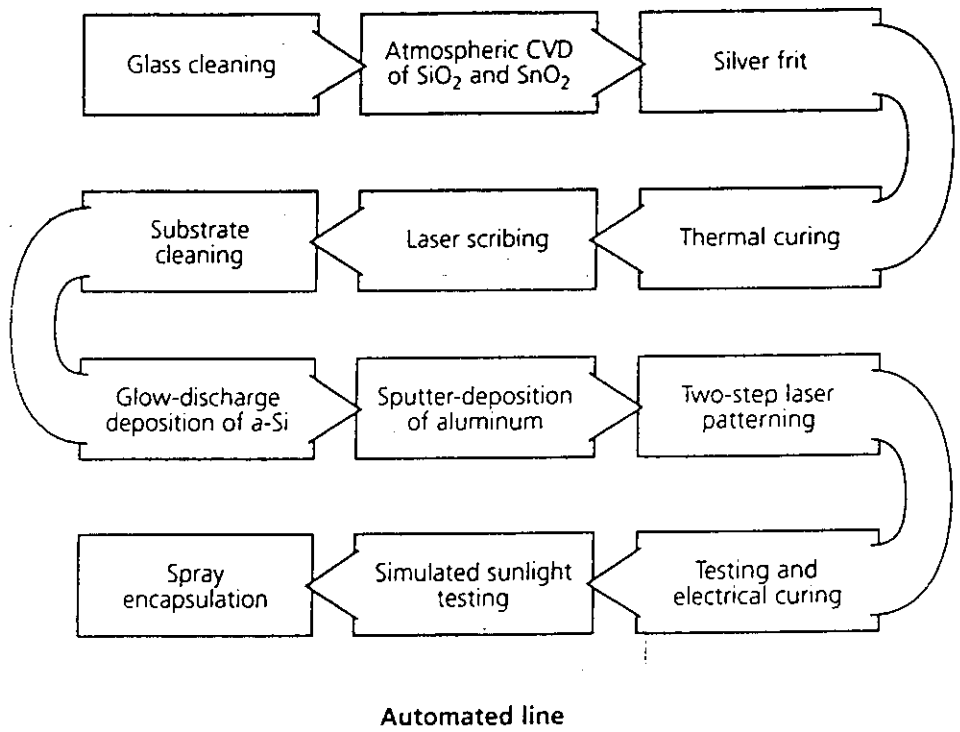

Fig. 1(a) *The flow chart of a totally automated manufacturing line operating in Newtown, Pennsylvania (Solarex Thin Film Division).*

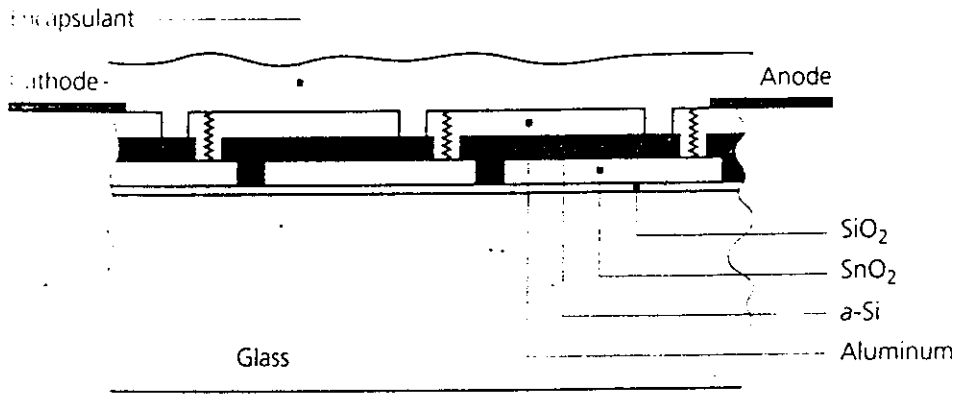

Fig. 1(b) *Diagram showing the interconnect region of a series-connected a-Si photovoltaic module.*

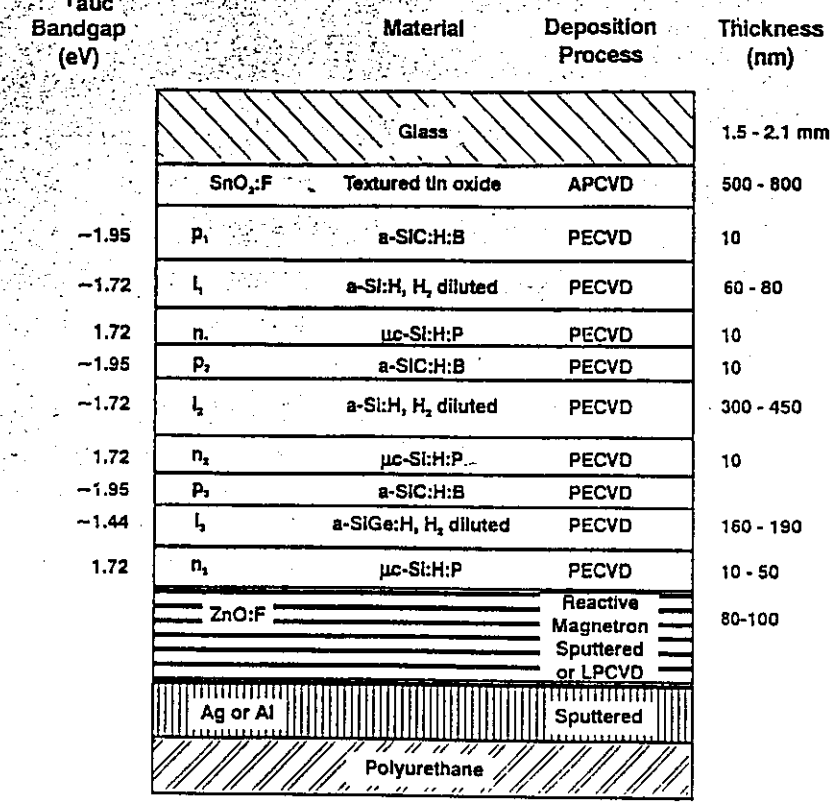

Figure 2. Typical triple-junction a-Si cell structure

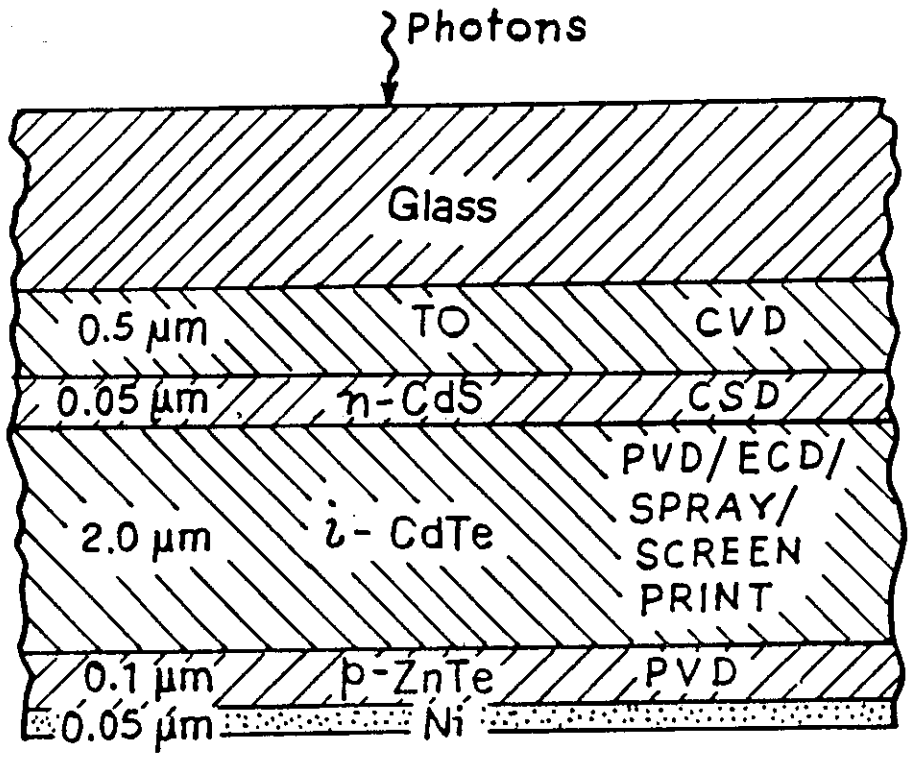

Fig..3

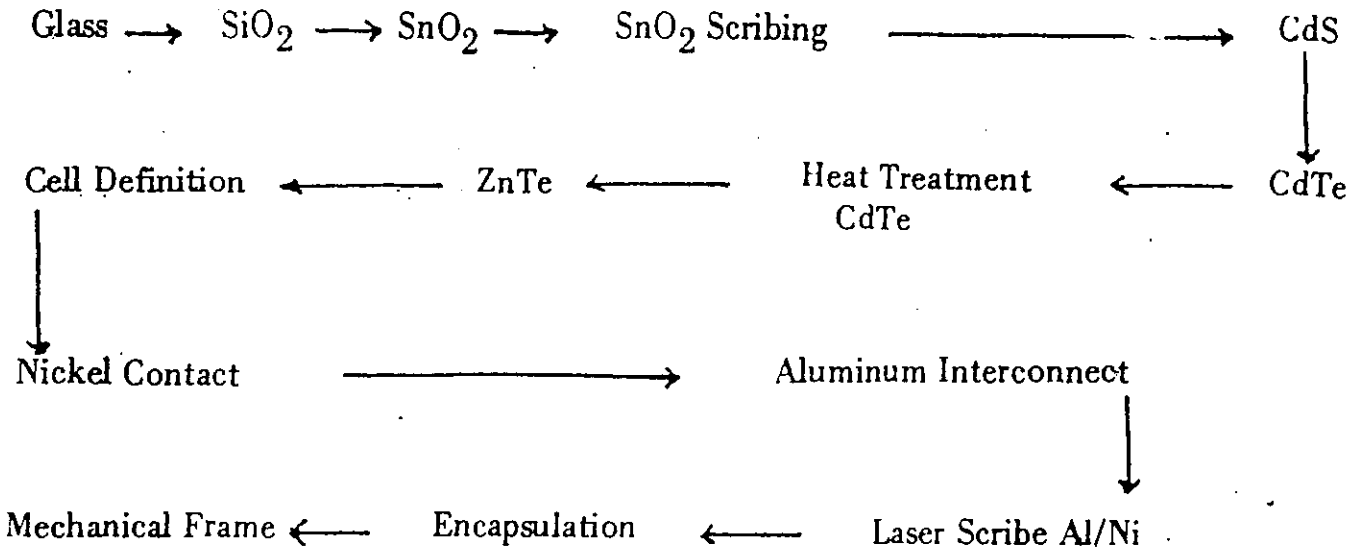

Fig. 4 *CdTe Cells (Ametek) process flow sheet*

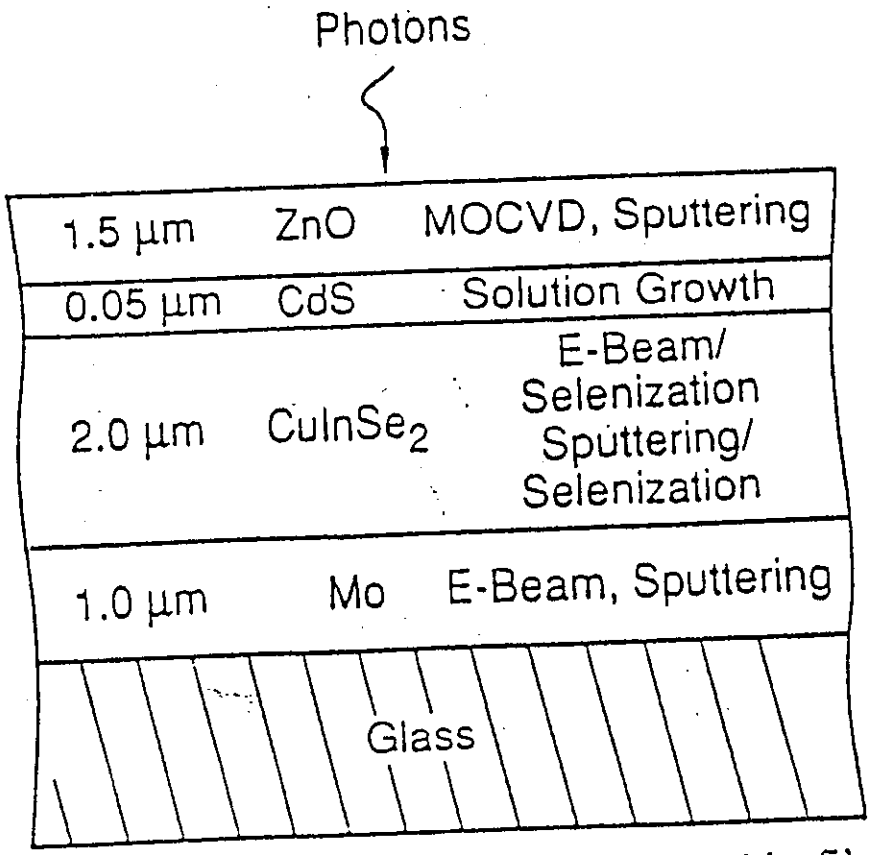

Figure 5 Solar cell structure of thin-film CIS device

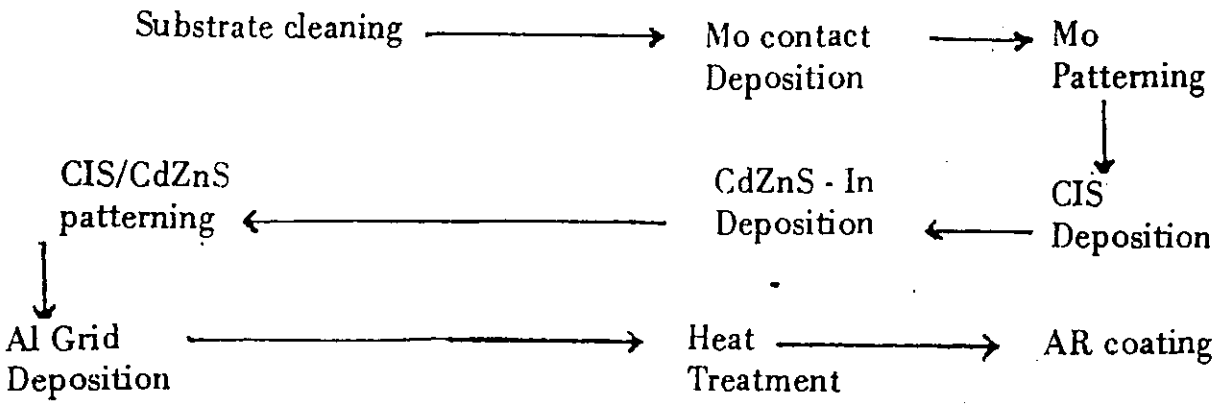

Fig. 6 *CIS cell process flow sheet*