

Photovoltaic (PV) Technologies and Solar Electricity in Viet Nam

By Nang Tran

Abstract

Photovoltaic (PV) solar energy has reached an accumulated power of over 1 GWp and has become a profitable industry at a substantial annual growth rate of more than 30 %. Many features of this technology have made it potentially a new millennium industry : fast growing market, an expected business of over US\$ 100 billion by 2030, accessibility to the billions of people worldwide, and environmentally sound as a “green” source of energy . Major market segments of this industry are : consumer applications where the module price is determined by price/ piece ; remote industrial systems where highly reliable , long lifetime and good efficiencies power sources are needed ; electricity in the developing countries where people still live without electrical light and other amenities of the industrialized world .

In this report, we will first present the leading terrestrial photovoltaic (PV) technologies, their performance , market potential and general trends to lower the cost to bring the PV solar electricity down to an affordable level to everybody . The latter basically follows a trend that is something similar to Moore’s Law in the semiconductor industry (although at much slower pace!) , that is , cost per device unit decreases significantly with the number of units produced in the mass production . In the foreseeable future, silicon solar cells continue to dominate the market whereas CdTe thin film cells are perhaps the only one which can meet DOE ’s goal of \$1.00/W_p . In the “high risk, high reward” category, dye sensitized nanocrystalline solar cells are considered as a potential candidate for a conversion efficiency of above 30% without concentrators, which will put PV solar in a competitive position in relation to other energy sources such as fossil and nuclear power.

At the end of the report, we will propose a model on how to fully harvest the PV solar energy in Viet Nam , a country with many sunny days and remote areas . We would like to suggest in this model a study of all the PV materials of the three generations , i.e. crystalline silicon (Generation I), polysilicon, thin film materials (Generation II) and advanced thin film materials (Generation III) . The level of efforts put on one set of materials over the others will be varied according to the phase in the program . Our first step will be the focus on the well – known PV crystalline silicon/ polycrystalline silicon solar cells / modules and use them as a reference to study the “nuts and bolts” of the PV technology such as the manufacturability, circuit design/ assembly , module packaging ,

large area uniformity , market potential, PV applications and to establish the infrastructure for the industry . Other thin film solar cells of Generation II and Generation III, especially dye sensitized nanocrystalline solar cells will be studied at the academic level first and will be gradually shifted to the prototype/production in terms of cost , performance and manufacturability using the knowledge , technology and the infrastructure we have gained from the development of crystalline silicon / polycrystalline silicon solar cells . Two technologies which are very critical in the manufacturing engineering of PV solar industry are believed to be the PV factory and the roll-to-roll process . Collaboration with the institutions and companies overseas will definitely help speeding up the progress of our PV endeavor and could possibly shorten the time required to establish a strong and healthy PV industry in Viet Nam .

In a larger scale, PV technologies will also be used as a stepping stone for Viet Nam to move into other “high tech” applications in the future . Besides renewable energy, other potential applications of nanotechnology in medicine , nanosensors, nanoelectronics and battery is the subject of interest that the research institutions should focus their efforts on . Thin films, nanotechnology, device physics and many others will put Viet Nam in a good position in establishing a knowledge economy . “There’s plenty of rooms “ for filing patents in many areas of science and technology .

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Photovoltaic solar energy is attractive due to the many attributes : abundant and indigenous sun energy resource , no or a few moving parts therefore low operating cost, capability to be assembled as modular ranging from a few watts to megawatts , low noise and low carbon dioxide emission. The PV system is reliable with low maintenance and generally has a lifetime of 20- 30 years as in the case of crystalline silicon solar modules. From the business point of view, the market of PV solar is exponentially exploding to a multi-billion dollar market size in the last decade. Another attractive feature of this “ green energy” is that it can be used in many innovative ways to adapt to different locations ranging from remote areas of the third world countries to commercial buildings and/or residential homes of the industrialized countries . The world market of PV solar energy has increasing significantly in the last decade as

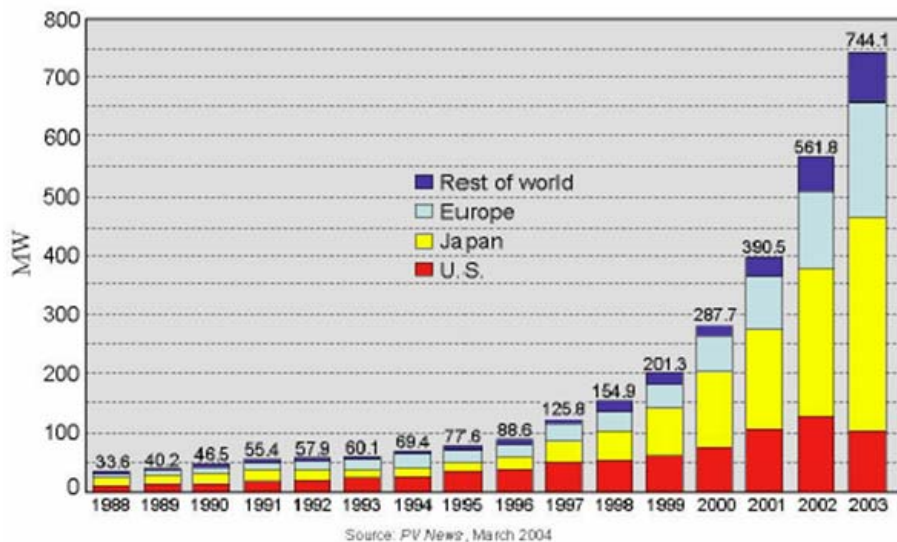


Fig. 1 PV world production [1]

shown in Fig.1 . The total world production has increased at a speeding rate from 201.3 MW_p in 1999 to 1200 MW_p in 2004. It is projected that the market trend will go from \$ 1.5 billion in 1999 to \$15 billion in 2010 and reach \$ 1.5-2 trillion in 2030 at an average annual

College of Science & Engineering, University of Minnesota, 200 Union St. SE, Minneapolis, MN 55455, USA . e-mail: binh_an_tran@hotmail.com

Invited paper to be presented at the First International Workshop on Nanotechnology and Applications, Vung Tau, Viet Nam, November 12-14, 2008.

growth of 35-40% . Large increase in the production has resulted in a rapid decrease in price of modules and systems. In 2010, Japan, Germany and US have plan to reach a production level of : 4. 82 GW , 2 GW and 3 GW , respectively [NREL] .

There are four major candidates for low cost, high performance photovoltaic solar modules :

(i) *first generation (Generation I)* : the standard wafer silicon materials (crystalline silicon) ; well understood material . High carrier mobility with a band gap of 1.1 eV.

(ii) *second generation (Generation II)* : polycrystalline silicon, thin film hydrogenated amorphous silicon (a-Si:H, band gap of 1.7 eV) and its alloys , copper indium gallium diselenide (CIGS, a band gap of 1.38 eV) and its alloys , and thin film cadmium telluride (CdTe, band gap of 1.58 eV). Advantages of this PV solar family is lower efficiency and lower manufacturing cost than crystalline silicon although the conversion efficiency has not reached crystalline silicon level yet.

(iii) *third generation (Generation III)* : organic solar cells , dye sensitized solar cells (DSSC) and quantum dot/ nanowires dye sensitized cells . Working mechanism is different from that of crystalline silicon ; there is not a p-n junction to separate the charges. Nanostructures have been increasingly used in this cell family . Advantage of this solar family is potentially low material cost . The degradation of polymer over time is still of concerns to many people in the field.

(iv) *fourth generation (Generation IV)* : hybrid inorganic nanocrystals mixed in polymers.

As compared with crystalline /polycrystalline silicon , thin film materials and advanced thin films in Generation II and III have some unique attributes which make them a better fit for newly developed trend of building integrated photovoltaic applications (BIPV) because of their flexibility in sizes , less consuming materials, and aesthetic appearance . Furthermore, significant progress has been made in the area of thin film solar modules with record laboratory efficiencies . Particularly, copper indium gallium diselenide thin film solar cells have reached a conversion efficiency of 19.5 % [NREL] and cadmium telluride thin film modules have been produced in mass volume with the potential of reaching the price goal of US\$1.00/ W_p for the first time in a couple of years [First Solar] .

Fig. 2 shows the efficiency, cost per peak watt (cost figure merit US\$/ W_p) for the three generations of PV solar modules .

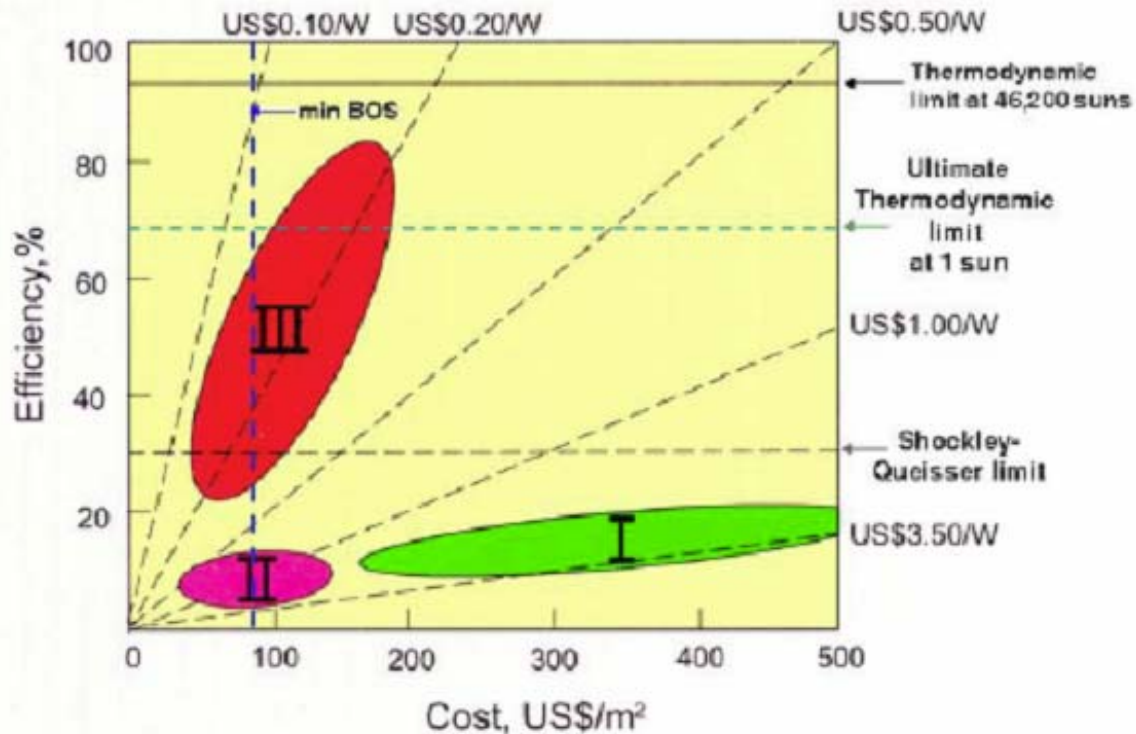


Fig. 2 shows conversion efficiency (%) , cost per unit area (US\$/m²) for the three generations of PV solar cells [2] .

The cost figure of merit (US\$/W_p) is calculated as the ratio of the module cost per unit area (US\$/ m²) and the maximum amount of electric power (depending on the module efficiency) per unit area . Five dashed lines are indicators assigned to different cost figure of merits: US\$3.5/ W_p , US\$1.00/ W_p , US\$0.50/ W_p , US\$0.20/ W_p , and US\$0.10/ W_p . Due to the Shockley- Queisser limit, the lowest cost figure of merit that single crystalline silicon (Generation I) can reach is US\$1.00/ W_p . For generation II, although the cost per unit area is lower than that in Generation I , since module efficiency is lower , the overall cost figure of merit however remains essentially the same . In order to make a breakthrough in the cost figure of merit, one has to go to PV cells of Generation III .

1- Definitions and mechanism of PV technologies

1-1 Cell structure

A general structure of the crystalline silicon photovoltaic solar cell is shown in Fig. 3 . This is a photovoltaic device to convert sunlight into electricity . Upon exposure to the sunlight irradiation, electrons in the valence band jump into the conduction band, leaving behind holes ; thus hole-electron pairs are generated and separated by the electric field at the p-n junction . The holes and electrons are then collected separately at the contacts on the front and rear of the cell, resulting in a photocurrent which is delivered to an external load (a light bulb in this case) at an applied voltage . The photocurrent depends on the

collection efficiency of holes and electrons , whereas energy difference (electrical potential) determines the photovoltage which combines with photocurrent to generate electric power . Generally, this solar cell is made on a p-type silicon wafer which has a thin n-type diffused layer of about $0.2 - 0.5 \mu\text{m}$ to form a p-n junction . Antireflection coating is used to reduce the amount of light loss due to the reflection from the silicon surface . Contact bar and fingers are generally screen printed Ti-Pd-Ag . [3]

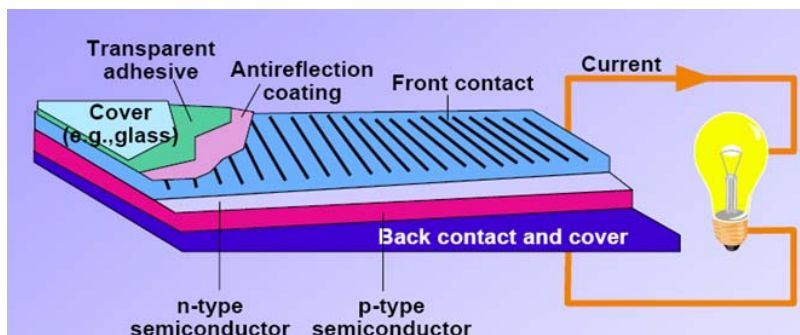


Fig. 3. General structure of PV silicon solar cell [3]

This general structure can be applied to other types of inorganic semiconductors and organic semiconductors . The main difference between inorganic and organic solar cells is that in organic solar cells, holes and electrons are initially bound to each other in pairs to form excitons ; the latter is broken apart to create holes and electrons for the generation of electric power.

1-2 Device parameters

Performance of the solar cell is evaluated based on the four main parameters : the short circuit voltage I_{sc} , the open circuit voltage V_{oc} , the fill factor FF and the conversion efficiency η . The short circuit current is the output current when the load impedance is much smaller than the device impedance , whereas the open circuit voltage is the output voltage which is obtained when the load impedance is much larger than the device impedance . Fill factor is the ratio between the maximum output power P_{max} over the incident power P_{in} .

A current- voltage characteristic curve for an illuminated solar cell is shown in Fig . 4 .

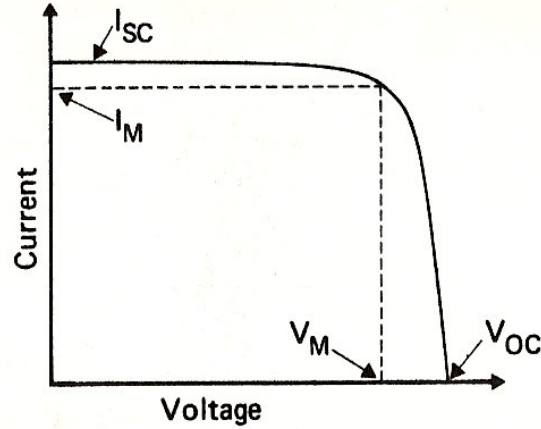


Fig. 4 . Current output vs. voltage output of a solar cell [3]

Numerically, open circuit voltage V_{oc} , short circuit current I_{sc} , the fill factor FF and the conversion efficiency η are expressed in the following equations ::

$$V_{oc} = \frac{AkT}{q} \ln[(I_{sc} / I_0) + 1]$$

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}} \times 100 \% \quad (1)$$

$$\eta = \frac{P_{max}}{P_{min}} \times 100 \%$$

In the above equations, A is the junction factor which is equal to 1 for a perfect junction, I_0 = dark saturation current, k = Boltzmann constant = $1.38 \times 10^{-23} \text{ J / K} = 8.617 \times 10^{-5} \text{ eV / K}$ and q = electron charge = $1.602 \times 10^{-19} \text{ Coulomb}$.

1-3 Definition of other components in a PV solar electricity system

A general structure of a PV solar electricity system is shown in Fig. 5 .

Where

Cell : basic building block

Module : building block in the field, a combination of many cells .

Array : Electrically connected modules.

The modules can be wired in series to increase voltage or in parallel to increase current . Not shown in this figure are the charge controller which is used to protect the battery from being overcharged and to eliminate any reverse current flowing from the battery to the solar modules and the battery is to store the charges .

Inverter : to convert to AC from DC should an AC power is required in some applications .

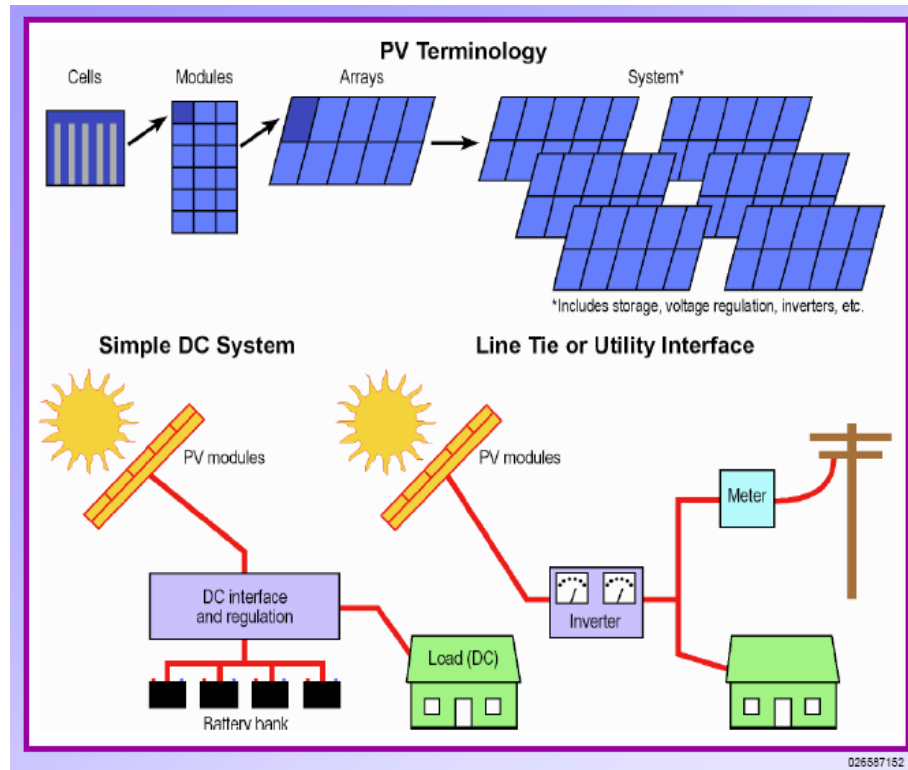


Fig. 5 A general structure of a PV solar electricity system [National Renewable Energy Laboratory –NREL , US Dept. of Energy].

Air mass : is used to describe how sunlight is modified by passing through the atmosphere . Values of the air mass (AM) are generally classified into three numbers:

- AM0 : The spectral distribution and the total flux just outside the Earth's atmosphere (outer space).
- AM1 : this number is measured at the equator at sea level at noon when incidence of the sunlight is vertical (sun at zenith) . The sunlight travels the shortest distance through the atmosphere and air to the Earth . The irradiance is $1,007 \text{ W/m}^2$.
- AM1.5 : mostly used at present in the PV industry , which is measured when the local atmospheric pressure is taken into consideration

$$p = 1.013 \text{ bar}$$

$$\text{The irradiance} = 1,000 \text{ W / m}^2$$

A general formula to determine the value of AM can be expressed as follows :

$$\begin{aligned} AM &= (\sin \alpha)^{-1} ; \alpha = \text{Incident angle} \\ AM^n &= (p / p_0) AM \end{aligned} \quad (2)$$

In the case of AM1.5 , n is 1.5, incident angle $\alpha = 42 \text{ degrees}$.

Bandgap : refers to the energy difference between the top of the valence band and the bottom of the conduction band . It is also the amount of energy required for the electrons to acquire to jump to the outside world . The band gap is closely related to the absorption coefficient which defines the extent to which a material absorbs energy and contributes to the photovoltaic effect in which number of electron-hole pairs are generated . Bandgap varies from material to material and can be engineered by alloying with different materials. For example, the bandgap of crystalline silicon is 1.1 eV whereas the bandgap of a-Si:H and GaAs is 1.7 eV and 1.4 eV, respectively . Fig . 6 shows the absorption coefficients of different solar materials , i.e. silicon, CIGS , cadmium telluride and GaAs . It can be seen from this figure that amorphous silicon, CIGS and CdTe have higher absorption coefficient than crystalline silicon , therefore having larger light absorption at a given thickness than crystalline silicon materials .

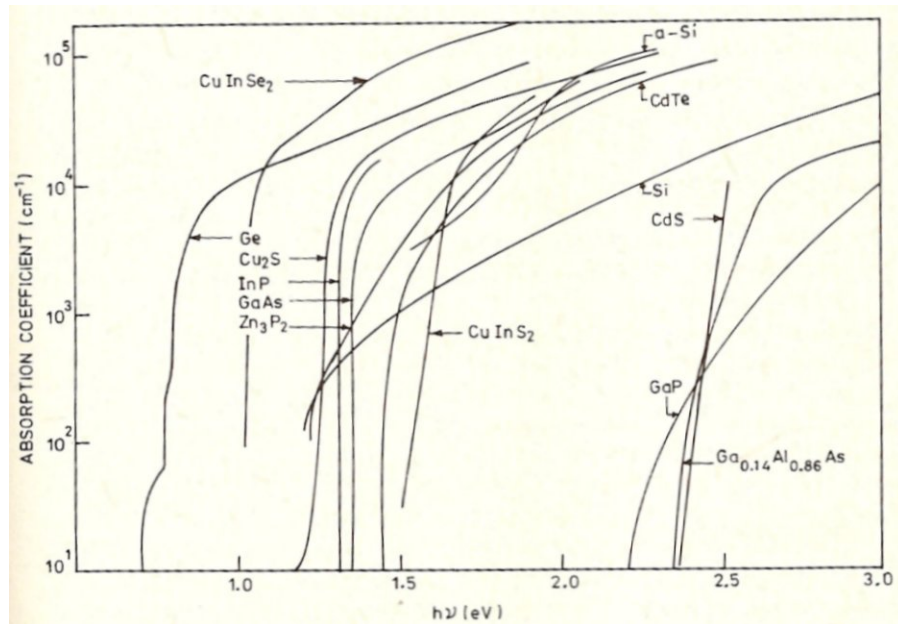


Fig. 6 . Absorption spectra of various solar materials [4]

Crystallinity : determine how ordered the atoms are . Definition of different types of crystallinity is shown in Table 1.

Table 1 : Definition of crystallinity

Type of crystallinity	Crystal size	Deposition method
Crystalline silicon	> 10 cm	Czochralski, float zone
Multicrystalline silicon	1 mm – 10 cm	Cast, sheet, ribbon
Polycrystalline silicon	1-10 mm	CVD
Microcrystalline	< 1 mm	Plasma deposition

2 - Crystalline silicon and polycrystalline silicon solar cells

2-1 Crystalline silicon

There are many principal candidates for PV solar cells : crystalline silicon, polycrystalline silicon, copper indium gallium selenide, cadmium telluride, dye sensitized solar cells and quantum dot cells . We will first discuss crystalline silicon and polycrystalline silicon which we refer both to as wafer silicon . This family of PV solar systems currently occupies more than 90 % of the total PV world market and is considered by many as the king of the PV solar energy at present and in many years to come . The technology is well studied , the mechanism is well known partly due to the long history of silicon PV solar

electricity but mainly due to the significant progress of semiconductor industry where silicon has been a dominant player in several decades .

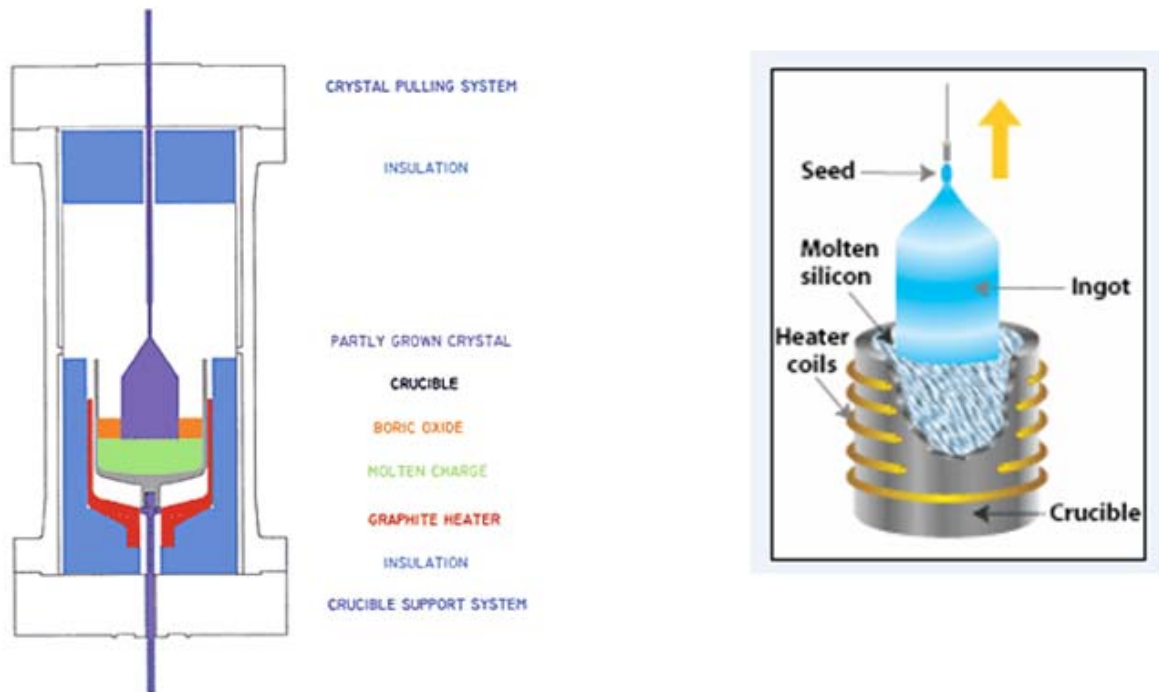


Fig. 7 . Czochralski process to grow crystalline silicon [Source : Wafertech]

Fig. 7 shows a Czochralski process to grow crystalline silicon . High purity silicon with a few parts per million of impurities is melted down in a crucible . Dopant material of a predetermined amount such as phosphor and boron is added to the molten intrinsic silicon to form a n-type or p-type silicon . A seed crystal is attached to a rod and is pulled upwards while being rotated at the same time . By precisely controlling the temperature gradient, rate of pulling and speed of rotation, one can extract a large, single-crystal, cylindrical ingot from the melt.

2-2 Polycrystalline silicon

Silicon wafers made from the Czochralski technique are usually in a circular shape , which generate gaps between the cells when the latter are assembled in a large number. Cutting the circular shaped silicon wafer into a rectangular shape generates silicon material loss and is therefore not particularly practical . The casting technique for making rectangular silicon such as Heat Exchange

Method (HEM) has been studied by for example Semix, Wacker Chemitronic and Silso and polycrystalline silicon (not crystalline silicon) has been obtained. The drawbacks of the above techniques such as a large amount of silicon material are used, material loss due to slicing into wafers compounded with chemical etching and grinding operations contribute to a large increase in the material cost. This had led Mobil Tyco Solar Energy Company in USA develop the edge-defined film fed growth (or EFG), a technique of making ribbon silicon for solar cells. With this process, one was able to manufacture silicon ribbon of a length of 50 m long and a production of 10-20 kW/month PV electricity at a cell conversion efficiency of more than 10% in 1975. In the last few years, another technique for making silicon ribbon which has drawn much attention is the string ribbon which has been developed by EverGreen Solar. Fig. 8 shows a process of making the ribbon. In this process, two wires are pulled vertically through a silicon melt and the silicon spans and solidifies between the strings to form polysilicon ribbon.

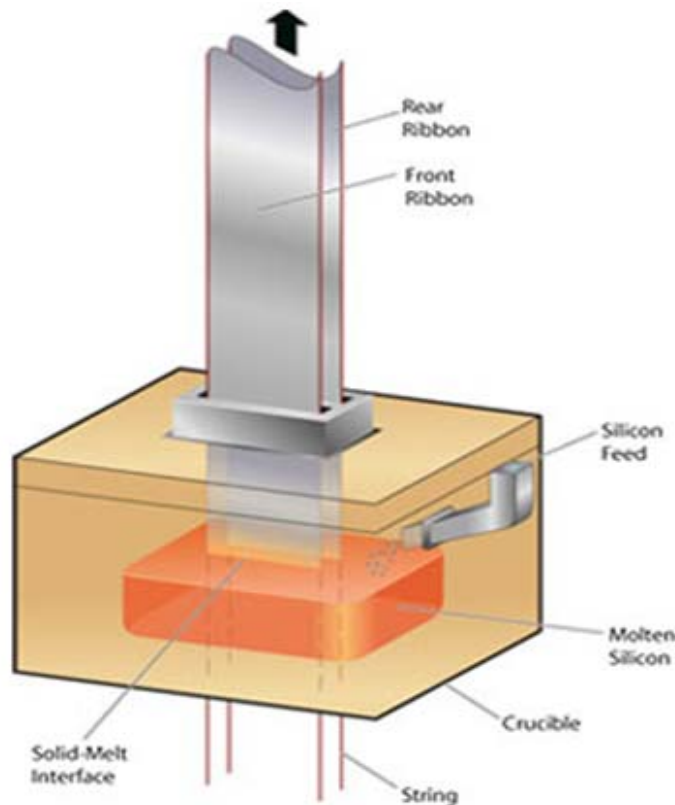


Fig. 8. String ribbon approach to grow polycrystalline silicon (Source : Evergreen Solar).

2-3 Sanyo 's HIT Cell

The HIT cell is perhaps the highest performance solar cell in the silicon family so far with a conversion efficiency of 22% over an area of 100 cm^2 . Other performance parameters are : $V_{oc} = 0.722\text{V}$, $I_{sc} = 38.6\text{mA/cm}^2$, $FF = 78.8$. This cell is different from the conventional crystalline silicon solar cell in that doped amorphous silicon and undoped microcrystalline silicon layers surround the crystalline silicon to reduce the combination loss of the charge carriers. Another features of HIT cell are optical confinement and low temperature coefficient, which together has enhanced the performance of the cell.

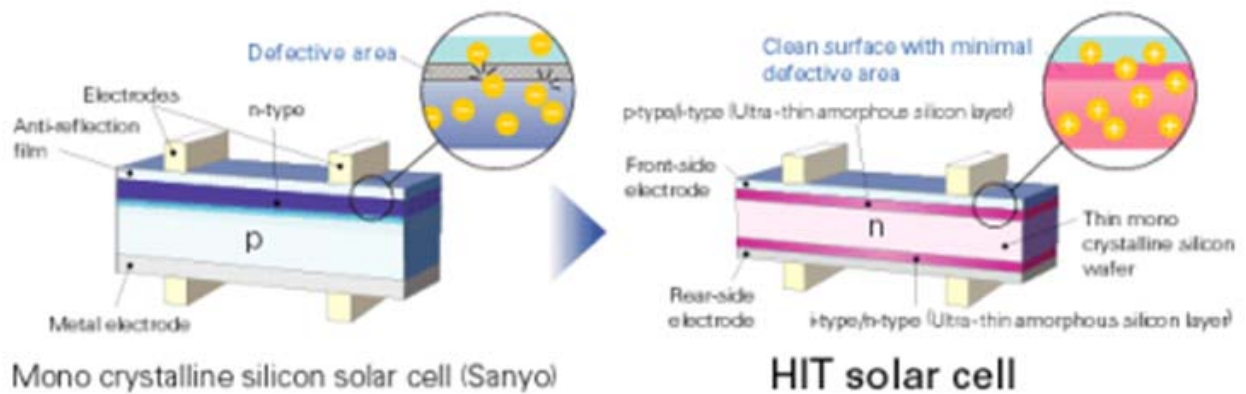


Fig. 9. HIT cell developed by Sanyo. The work was partially funded by NEDO of Japan (New Energy and Industrial Technology Development Organization).

Fig. 9 shows a general structure of the HIT cell (on the right side). Structure of a conventional crystalline silicon solar cell is shown on the left side for reference. Fig.10 indicates gain in the absorbing spectrum mainly due to the optical confinement. Sizes and shapes of the textures are optimized for maximum effect in the optical confinement. Whereas, interface between crystalline silicon and amorphous silicon layers are improved by silicon surface cleaning and damage reduction during the coating of amorphous silicon layer.

Another view of HIT Cells

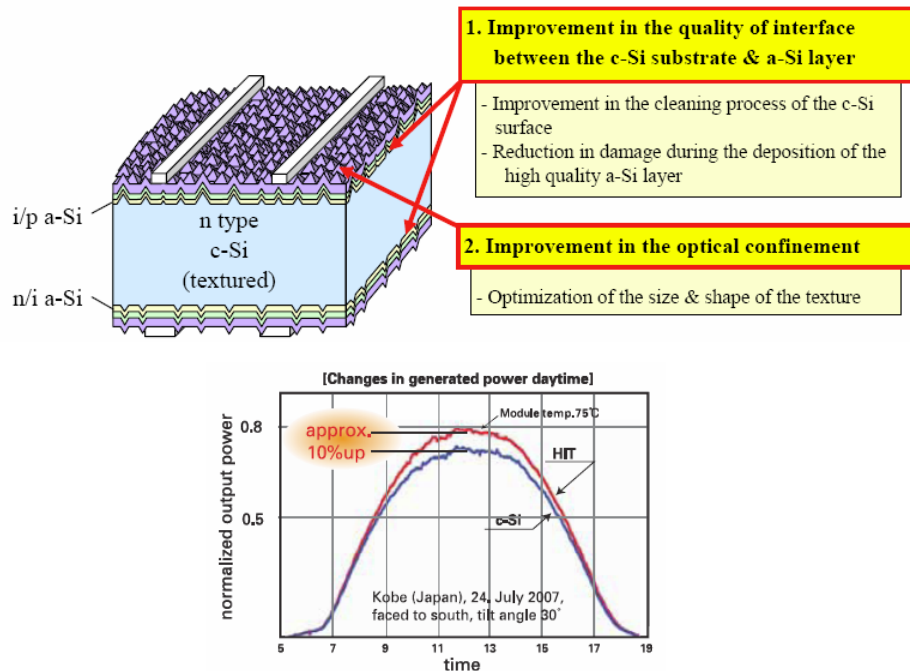


Fig. 10 . Performance of HIT solar cells are enhanced by the optical confinement and by cleaning of crystalline silicon surface [Source :Sanyo] .

3- Thin film Amorphous silicon

Amorphous silicon (hydrogenated amorphous silicon or a-Si:H) has several advantages : (i) since the process temperature is low (200-300 C), it can be coated on flexible substrate or low melting temperature glass , (ii) high absorption coefficient in the visible range , making the total module thickness of amorphous silicon is much thinner than the module thickness of crystalline silicon (about 1/600) as shown in Fig. 11 , (iv) radiation resistant and (v) the process can be integrated monolithically in one coating and (vi) can be made semi-transparent, enabling it to be appropriately used for many BIPV applications (Building Integrated Photovoltaics) . One of the major drawback of amorphous silicon solar cells is the Staebler –Wronki (S-W) effect – light induced degradation which holds the module conversion efficiency back in the range of 6-8%. One way to reduce this S-W effect is to form a multi-junction cell with thinner intrinsic layers. This tandem cell can be made with materials of different band gaps to maximize the amount of absorbed energy as illustrated

in Fig .12. This tandem configuration consists of three layers of three different band gaps, i.e. $E_{g1} > E_{g2} > E_{g3}$. Materials of different band gaps can be engineered by changing the amount of germanium (Ge) , tin (Sb) or hydrogen in amorphous silicon matrix or by changing the morphology of amorphous silicon to microcrystalline silicon as can be seen in the triple –junction tandem cell designed and fabricated by United Solar.

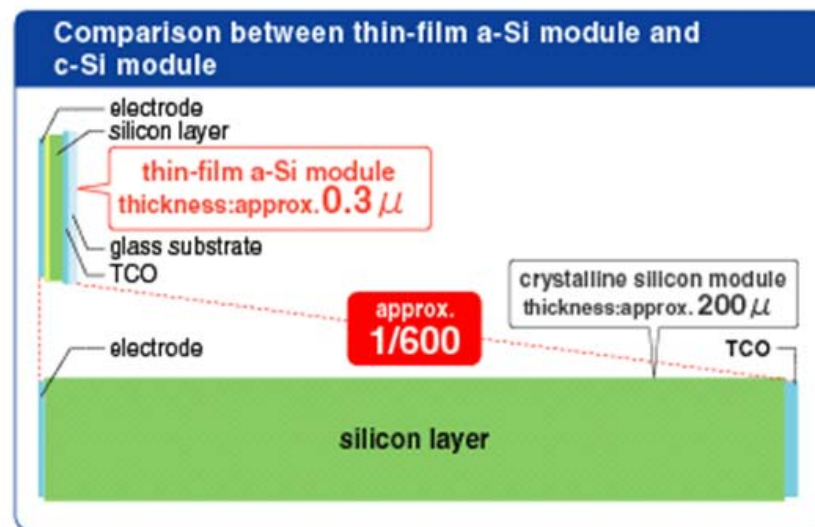


Fig. 11 . A-Si module thickness is about 1/600 of crystalline silicon module thickness due to a large difference in absorption coefficients of the two materials [Source : Sanyo]

Tandem Cells

Different semiconductor materials will be arranged one on top of the other to decrease the amount of energy lost during absorption.

$$E_{g1} > E_{g2} > E_{g3}$$

General schematic

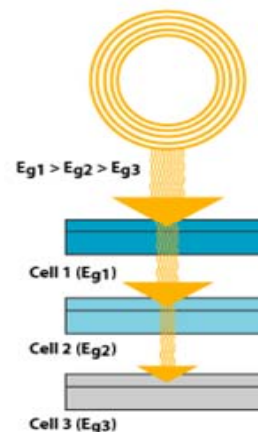


Fig. 12 . General concept of a-Si based tandem cells .

Structure of an amorphous silicon solar cell is shown in Fig. 13 for two main configurations : Schottky barrier or MIS (Metal Insulator Semiconductor) type and the n-i-p (or p-i-n) type .

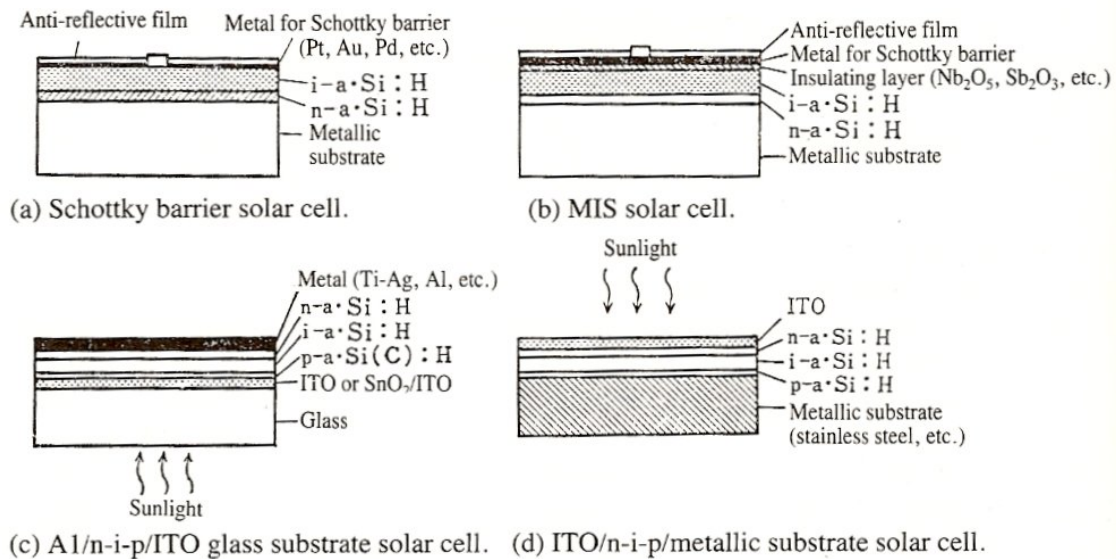


Fig.13. Typical amorphous silicon solar cell structures (5) .

A general structure of a-Si based triple- junction tandem cell is shown in Fig .14 . a-Si:H and a-SiGe films are used for the large bandgap and narrow bandgaps, respectively and ZnO and ITO transparent conducting oxides are used for the contact electrodes.



Fig. 14 . A triple junction a-Si:H based silicon solar cells
[Source : United Solar]

There are two types of substrates for amorphous silicon solar cells and modules: rigid substrate (glass substrate) and flexible substrate (stainless steel , polyimide) . Many companies are working on glass substrate; and some on stainless steel . In an attempt to further reduce weight of the solar modules, our group at 3 M , in a cost- sharing contract with NREL (Department of Energy, 1984-1987), had developed amorphous silicon solar cells on polyimide . AS an example, cells of a p(200 Å)-i(4,500 Å) -n (300Å) configuration (Fig. 15) were coated in-line on a web of 2 mil thick and 4 inches wide in a plasma enhanced chemical vapor deposition, as shown in Fig. 16. The web was outgassed , cleaned , sealed and precoated with Al/TiN in a Web Pre-treatment System (PTS). Undoped layer (i layer) had photoconductivity values greater than $1 \times 10^{-4} (\Omega - cm)^{-1}$ under AM1 illumination and the obtained cells had an efficiency of 9% over an area of 1 cm^2 . The p window layer was also a wide band gap p-SiC layer with a composition gradient at the p/i interface . When dealing with polyimide , one has to pay special attention to the contamination which is caused by the two following mechanisms : (i) the web is not completely cross-linked and (ii) outgassed web will absorb water during the web transfer process. In our PTS system , the web was first sent through an oven section at 300 C for outgassing trapped water and curing. And both sides of polyimide were coated with at least one layer of metal back electrode .

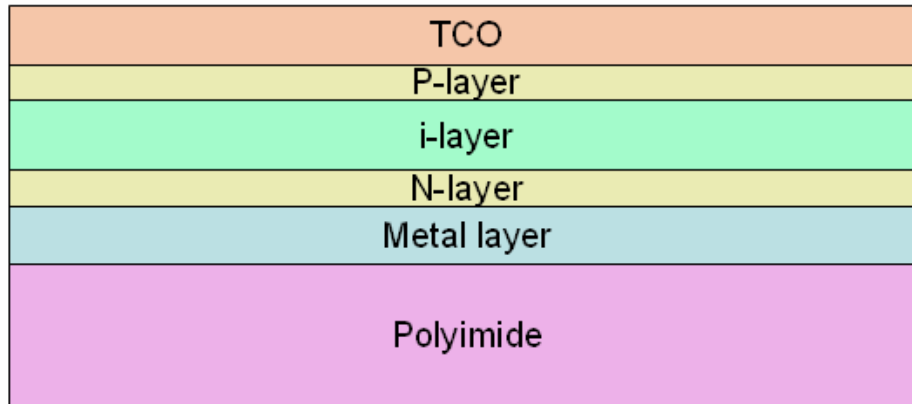


Fig. 15 p-i-n amorphous silicon solar cell on a polyimide substrate . We also studied a n-i-p configuration (not shown here).

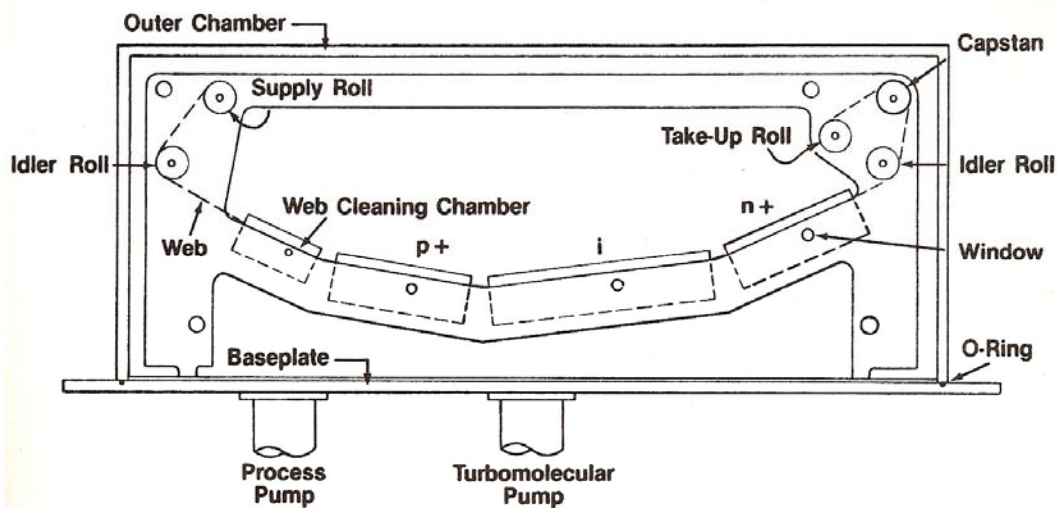


Fig. 16. An in-line plasma enhanced chemical vapor deposition for coating p,i,n layers of amorphous silicon .Standard deposition conditions : n-chamber : $H_2 = 81$ sccm, $SiH_4 = 0.6$ sccm, $PH_3 = 0.006$ sccm, 30 W, 210 C, 1 Torr, deposition rate of 12 Å/min. ; i-chamber : $H_2 = 160$ sccm, $SiH_4 = 56$ sccm, $B_2H_6 = 56 \times 10^{-6}$ sccm, 30 W, 230 C, 1 Torr , deposition rate of 133 Å/min ; and p-chamber : $H_2 = 58$ sccm, $SiH_4 = 0.3$ sccm, $B_2H_6 = 0.006$ sccm, 40 W, 210 C, 1 Torr, deposition rate of 8.8 Å/min . [Source: 3M & NREL] .

Modules were made using a combination of insulating/ conducting epoxy printing and laser scribing/ diffusing as shown in Fig 17.

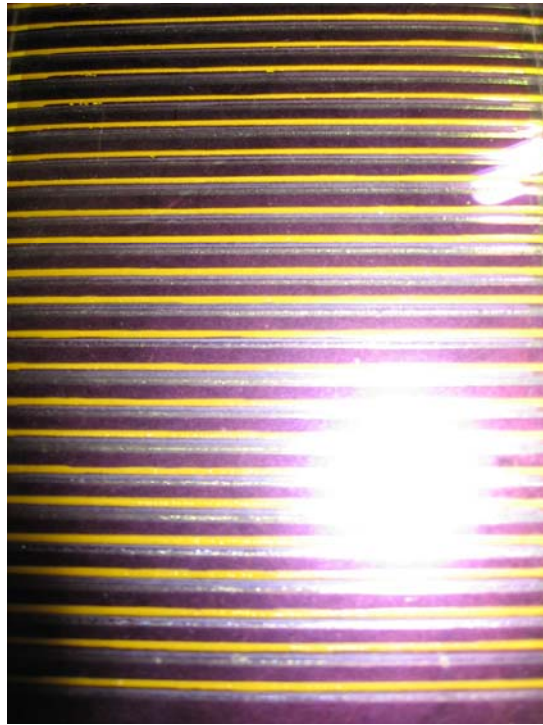


Fig. 17. Amorphous silicon solar module on a flexible polyimide substrate
[Source : 3M & NREL]

4- Zinc oxide transparent conducting oxide as an electrode

In 1984 , a new type of transparent conducting oxide was developed at ARCO Solar by the author and his co-workers [6] . This new type of oxide thin film is zinc oxide (ZnO) doped with group III elements (Al, Ga, B) in combination with with hydrogen in some case . The obtained ZnO has a low absorption coefficient and high transmission , therefore can be made thick (2- 3 μm) for better conductivity . As a result, the newly developed ZnO film has been widely used in many amorphous silicon and copper indium diselenide cell structures even to this date.

Fig. 18 shows an average optical transmittance of 85% over a wavelength range of 400 to 1100 nm and a resistivity of $4.9 \times 10^{-4} \Omega - \text{cm}$. The Hall mobility and the carrier concentration were measured in the temperature range of 300 to 77 K, which was $34 \text{ cm}^2 / \text{V} - \text{sec}$ and $2.8 \times 10^{20} \text{ cm}^{-3}$, respectively.

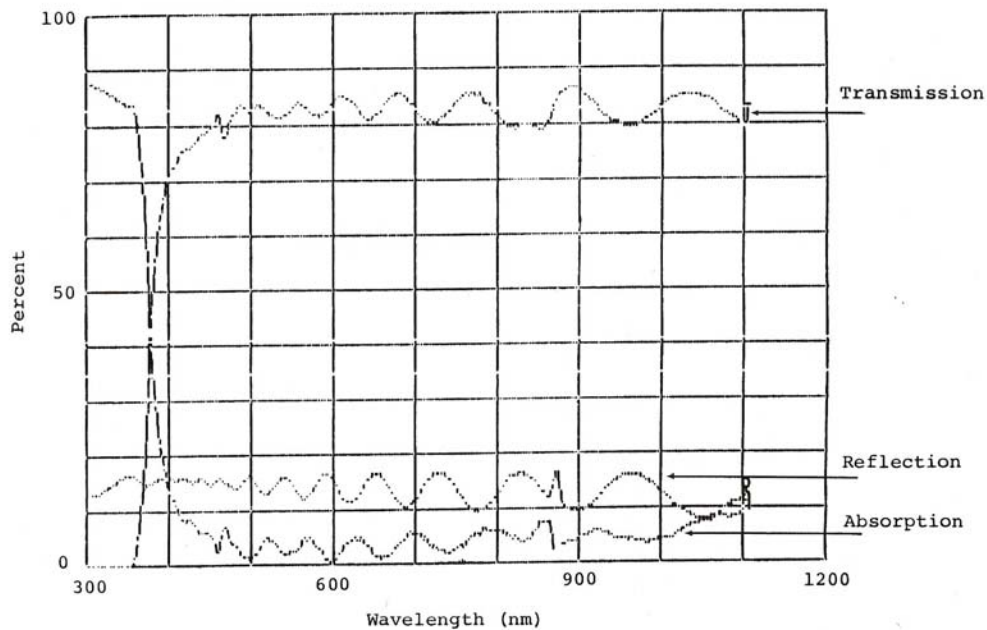


Fig. 18. Optical transmittance of sputtered ZnO (Al, H) film as a function of the wavelength (ARCO Solar, 1984)

A novel device structure of ZnO (Al)/CdS/CuInSe₂/Mo as shown in Fig. 19 was fabricated on a glass substrate. A thick sputtered ZnO (2.2 μm) was deposited onto the evaporated CdS/ CuInSe₂ stack of films at an ambient substrate temperature. A 9.6% conversion efficiency over an area of 1.9 cm² was demonstrated, as shown in Fig. 20. It should be noted that other transparent conducting oxides (TCO) of the above thicknesses of 2.2 μm have a low transmission, reducing the amount of current flowing through the cells. A similar conversion efficiency (10%) was also obtained on ZnO/pin a-Si/Al over an area of 4 cm². ZnO transparent conducting films were also fabricated using the chemical vapor deposition (CVD); molybdenum film was sputtered and CuInSe₂ was prepared by first sputtering Cu and In layers sequentially, followed by the selenization process in the presence of H₂Se gas mixture.

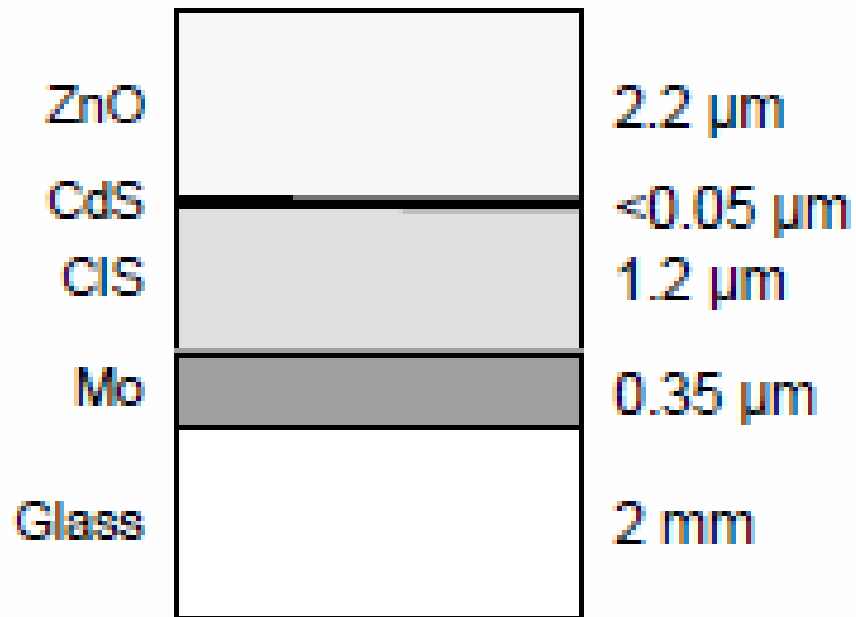


Fig. 19 A general schematic diagram of the ZnO/ CuInSe₂ solar cell [Source : ARCO Solar] . A thickness of 2.2 μm was much thicker than conventional TCO films for the same light transmission .

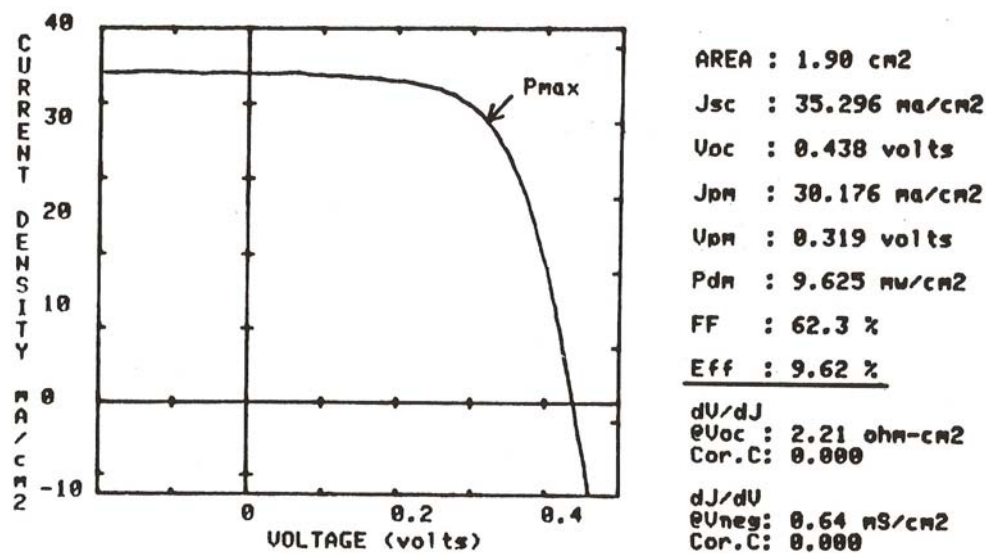


Fig. 20. Illuminated current-voltage characteristics of the historic ZnO/CdS/CuInSe₂/Mo solar cell on a glass substrate [ARCO Solar, 1984, External publication No 85-22A/EA]

ZnO enhanced the conversion efficiency of polysilicon solar cells (25 cm^2) over other transparent conducting oxide films. As in the case of polysilicon solar cells, short circuit current density J_{sc} was increased to 28 from 22.86 mA/cm^2 ; conversion efficiency to 13% from 10.81% while the open circuit voltage V_{oc} remained the same at 0.597 V (Fig. 21).

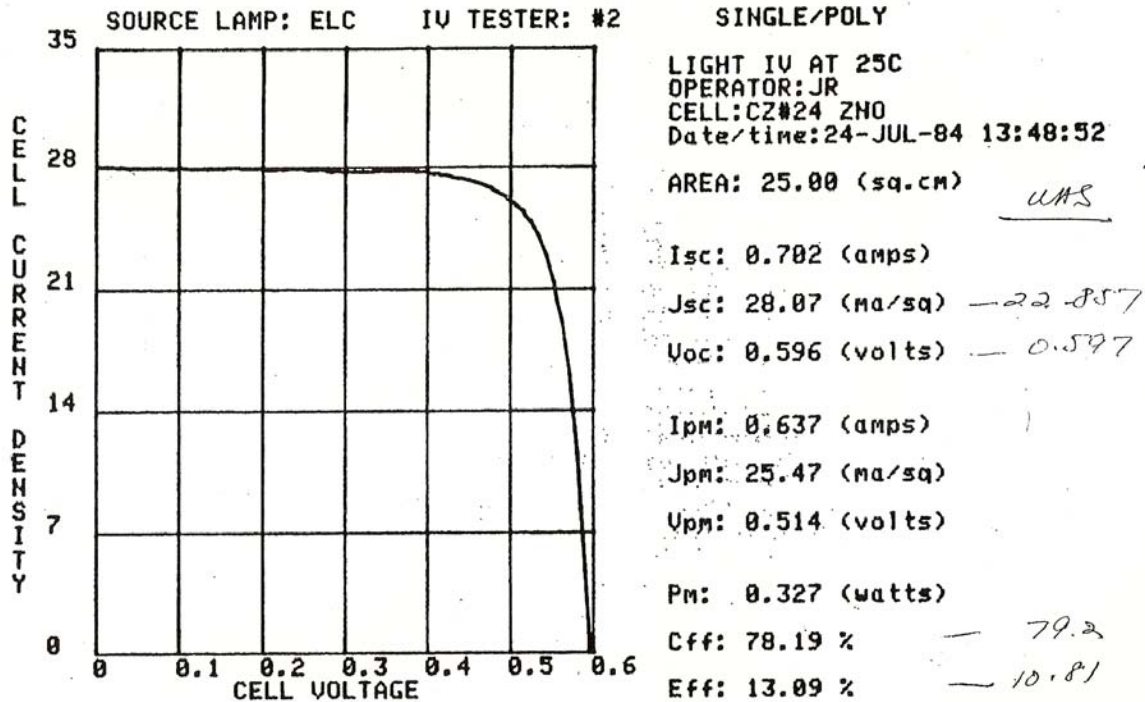


Fig. 21. A conversion efficiency of 13% was obtained with ZnO / polycrystalline silicon [ARCO Solar, 1984].

The above numbers of solar cells with ZnO electrode were considered among the best (if not the best) conversion efficiencies at that time.

5- Thin film silicon

One approach to reduce the cost is to reduce thickness of the silicon material in the solar cells. Several approaches have been tried in many laboratories. The first approach is to coat a thin high quality silicon layer on a low quality silicon substrate; or depositing a thin layer of silicon then melted to be recrystallized into a high quality thin silicon layer. A general structure of the solar cell with this type of thin film silicon is shown in Fig. 22.

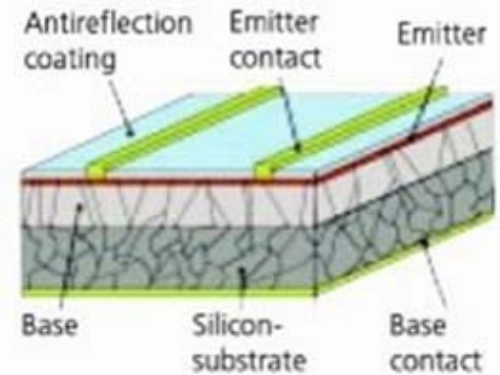
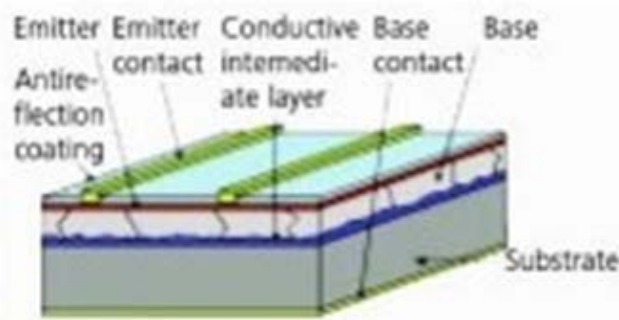


Fig. 22. A process of making thin film silicon [Source : Fraunhofer Institut Solare Energie Systeme] .

Another approach is the laser recrystallization of a metal –induced amorphous silicon film. The process can be described as follows : first a thin layer of 200 nm of amorphous silicon is coated on a glass substrate, followed by sputtering a layer of aluminum (200 nm) . The film was irradiated with an argon ion CW laser beam for recrystallization . Laser power density was ranged from 4-9 W/cm² . [ref.7]

6- Concentrator Photovoltaics (CPV)

The PV solar cells used for this concentrator applications are generally based on gallium arsenide (GaAs) , a material which has a band gap of 1.4 eV and can stand a higher temperature than that of silicon materials . This GaAs- based solar cell has reached a world record efficiency of being close to 40 % last year . [Source : SpectroLab] . This cell is more expensive but since only small area cells are used, the overall cost is expected to be cheaper .

A general structure of a CPV system having a cell conversion efficiency of 36 % (under concentration) at 700 suns is shown in Fig.23 . GaAs-based solar cells and an array of Fresnel lens (24 cm x24 cm each) were used for this CPV system . A closed-up look of the CPV is shown in Fig. 24 .

Concentrator Technology

(Solar Test & Research STAR)

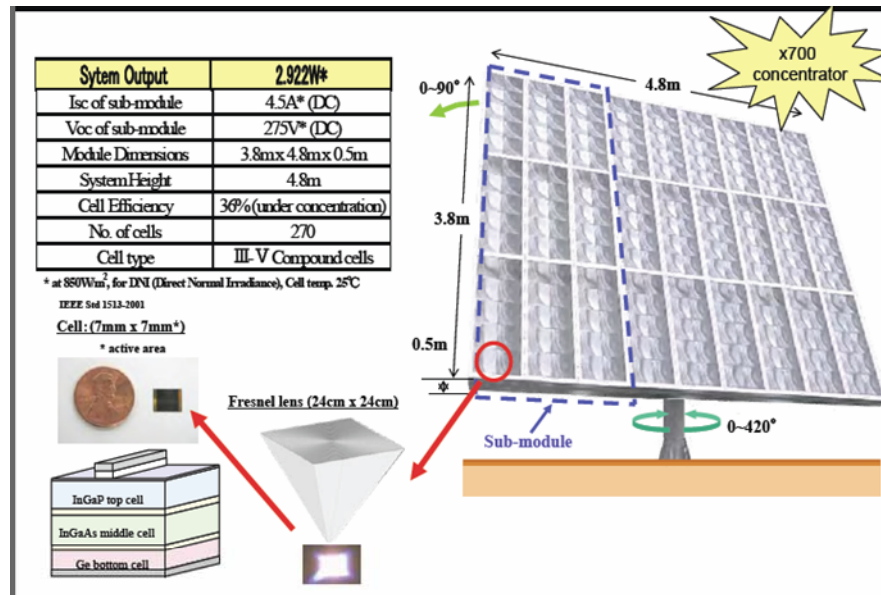


Fig. 23. A general view of the concentrator PV system [Source : Solar Test & Research STRAT]

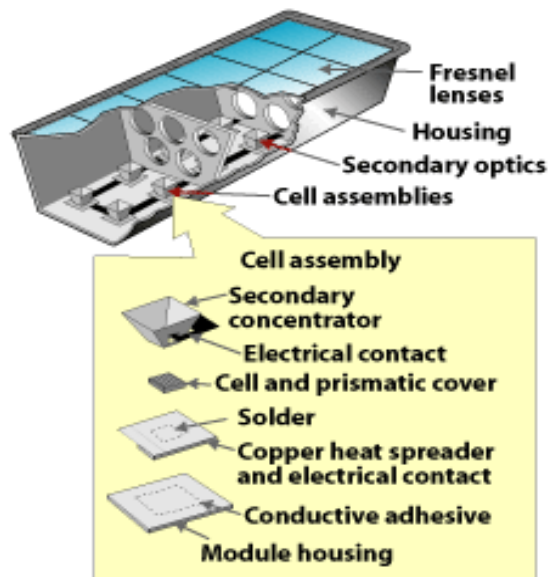


Fig .24. A closed –up view of the individual concentrator cell .
[Source : Solar Test & Research STRAT].

Advantages of concentrator PV are large scale power generation, high efficiency , less solar cell material and inexpensive plastic lens . The drawback is however the high heat generation which requires cooling .

7- Copper Indium Gallium Selenide (CIGS) and Cadmium Telluride (CdTe) Solar Cells

Schematic of CIGS and CdTe Solar Cells

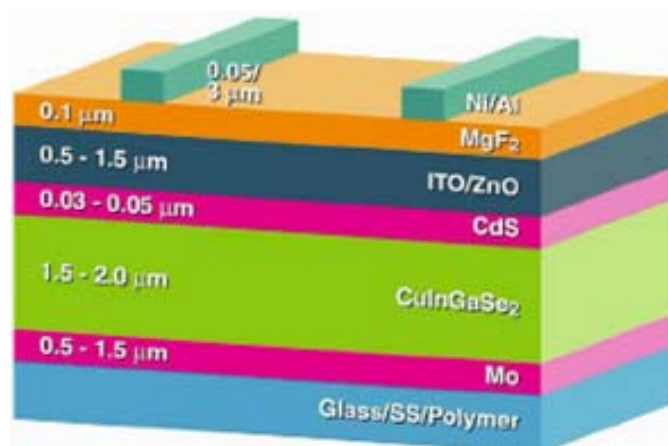
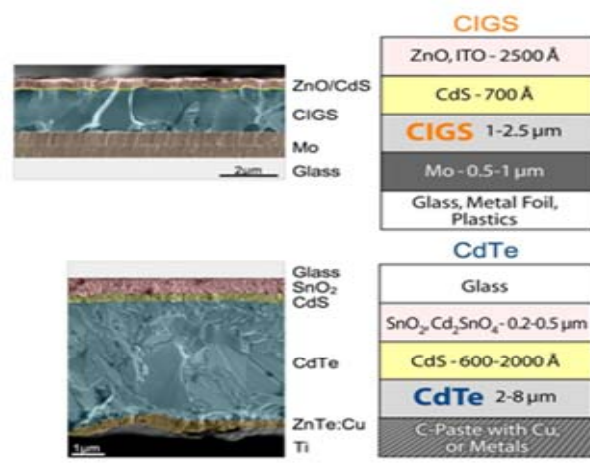


Fig. 25 . Structure of CIGS and CdTe solar cells
(Source :T .Surek, NREL)

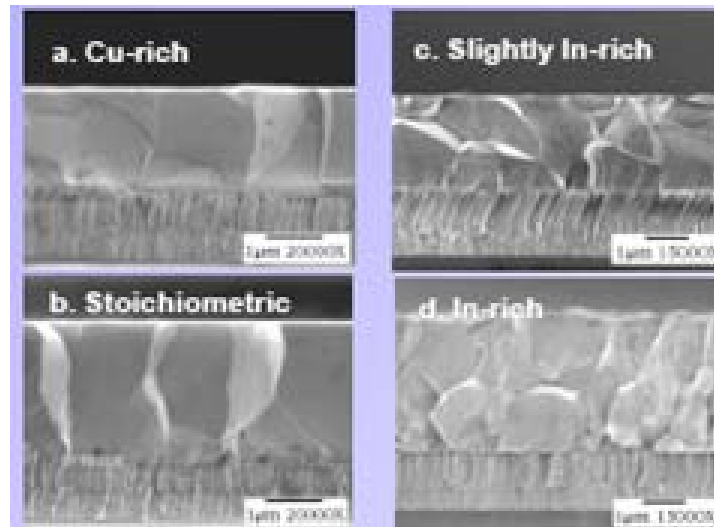


Fig. 26. Cu, In are critical in determining the CIGS morphology (T. Surek, NREL)

The CIGS can be deposited using practically any techniques such as co-evaporation, sputtering/ selenization, non vacuum/ wet chemical , printing and electrodeposition . The substrate can be glass, stainless still or aluminum foil . Except for the glass substrate, since sodium has some effect on the growth of CIGS , a sodium –contained source is generally incorporated when stainless steel or aluminum substrate is used. The selenization temperature is very critical in determining the morphology growth of a high quality CIGS film. The world record efficiency for thin films CIGS cell has been demonstrated by a group at NREL with a 19.5% laboratory scale with CdS and a 18.6 % efficiency with Cd-free ZnS . The prototype module has an efficiency of 13% but generally in the range of 9-11% in the commercial products and 10 years warranties . Structure and morphology of CIGS solar cells are shown in Figs 25 and 26, respectively.

In order to achieve high quality crystalline properties, control the quality of CdTe and CdS films is important. Role of Cu diffusion , annealing and heat treatment with CdCl₂ , back contacts have to be taken into consideration. How to handle cadmium safely and future short supply in indium are potential problems. So far the conversion efficiency is good; most importantly large scale production has already been in place . How to interface the compatibility of different manufacturing steps is still a challenge. As can be seen in the above figures , contents of indium and copper, selenization temperature are critical in determining the crystal growth quality, therefore the performance of CIGS cells. Another issue lies with the CdS coating process where the chemical batch coating seems to be the best empirically for a better CIGS - CdS interface .

Works are needed to be done on the process control for a large area and good reproducibility.

A structure of CdTe is shown in Fig.27 .

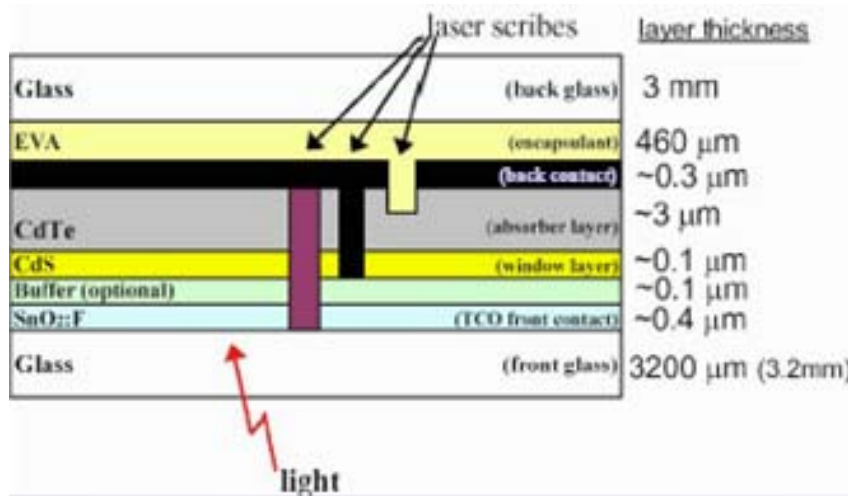


Fig. 27 . A structure of CdTe thin film solar cell [Source : First Solar] .

A cell and module efficiency of 16.5% and 11% , respectively and commercial products with an efficiency of 7-9% . , 10-20 years warranties have been demonstrated. Different coating techniques have been used : electrodeposition, close-spaced sublimation , CVD and sputtering . Effect of CdCl₂ on the morphology of CdTe film is shown in Fig. 28 .

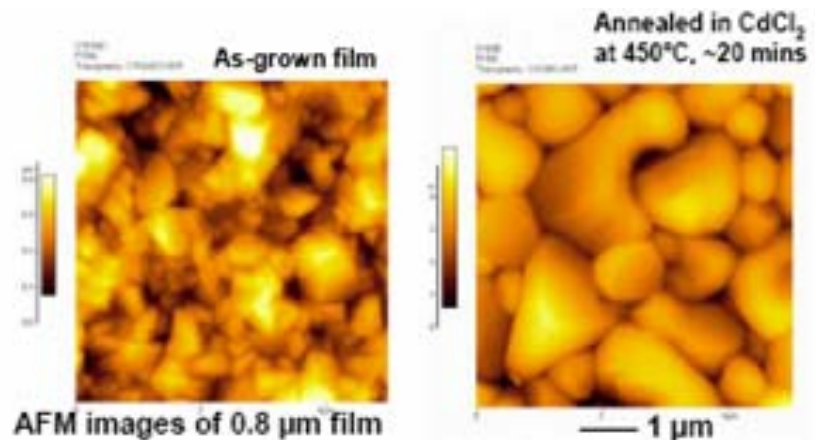


Fig. 28 . The critical role of CdCl₂ annealing .

Table 2. Performance of CIGS and CdTe solar cells (source :NREL)

	Area (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	Efficiency (%)	Comments
CIGSe	0.410	0.697	35.1	79.52	19.5	CIGSe/CdS/Cell NREL, 3-stage process
CIGSe	0.402	0.670	35.1	78.78	18.5	CIGSe/ZnS (0,0H) NREL, Nakada et al.
CIGS	0.409	0.830	20.9	69.13	12.0	Cu(In,Ga)S ₂ /CdS Dhare, FSEC
CIAS	—	0.621	36.0	75.50	16.9	Cu(In,Al)Se ₂ /CdS IEC, E _g = 1.15 eV
CdTe	1.03	0.845	25.9	75.51	16.5	CTO/ZTO/CdS/CdTe NREL, CSS
CdTe	—	0.840	24.4	65.00	13.3	SnO ₂ /Ga ₂ O ₃ /CdS/CdTe IEC, VTD
CdTe	0.16	0.814	23.56	73.25	14.0	ZnO/CdS/CdTe/Metal U. of Toledo, sputtered

High efficiencies of CIGS (where S is Selenium or Sulfur) and CdTe solar cells from different cell configurations and different laboratories are summarized in Table 2 and Table 3 . A module efficiency of up to 13 % had been demonstrated .

Table 3. Module efficiencies of CIGS and CdTe from different laboratories [Source :NREL]

Company	Device	Aperture Area (cm ²)	Efficiency (%)	Power (W)	Date
Global Solar	CIGS	8390	10.2*	88.9*	05/05
Shell Solar	CIGSS	7376	11.7*	86.1*	10/05
Würth Solar	CIGS	6500	13.0	84.6	06/04
First Solar	CdTe	6623	10.2*	67.5*	02/04
Shell Solar GmbH	CIGSS	4938	13.1	64.8	05/03
Antec Solar	CdTe	6633	7.3	52.3	06/04
Shell Solar	CIGSS	3626	12.8*	46.5*	03/03
Showa Shell	CIGS	3600	12.8	44.15	05/03

A summary of the conversion efficiency of CIGS and CdTe solar cells is shown in Fig. 29 (a) and (b) .

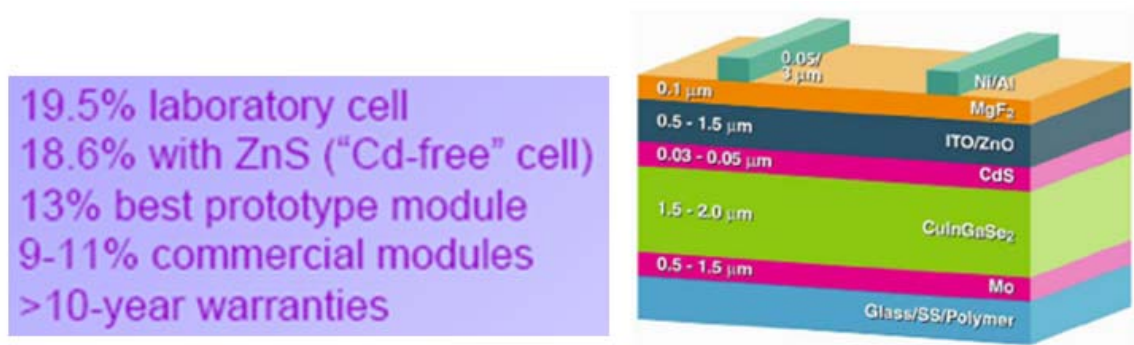


Fig. 29 (a) conversion efficiency of CIGS solar cells (Source : Surek, NREL) . Efficiency of the best module is about 67% of that of the best laboratory cell.

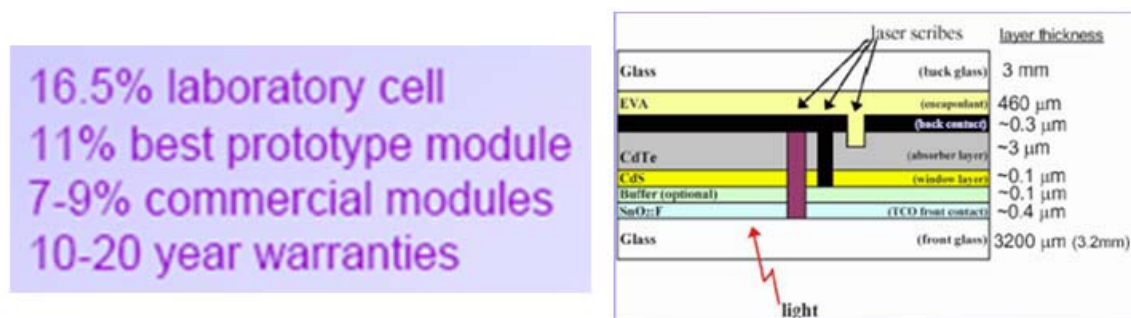


Fig. 29 (b) conversion efficiency of CdTe solar cells [Source : Surek, NREL] . Similar to CIGS cells, efficiency of the best module is about 67% of that of the best laboratory cell.

Although CIGS and CdTe thin film solar cells have exhibited a higher conversion efficiency than amorphous silicon solar cells . These two types of solar cells however have run into major drawbacks : short supply in indium for CIGS and toxicity of cadmium for CdTe .

8. Advanced thin film solar cells

Study indicates that advanced thin film solar cells such as dye sensitized solar cells, quantum dot solar cells have a potential to be less expensive than other types of solar cells because of the low temperature process, therefore flexible, and cheap substrates can be used .

Three major advantages of nanostructured materials / nanoparticles over the conventional materials are : (i) large surface and interface areas, therefore enhancing light absorption and charge separation, two important factors in PV solar cells ; (ii) tailoring optical properties by adjusting particle sizes and electrons and holes can be well confined and (iii) multiple exciton generation [8] , that is, a multiple of electron-hole pairs are generated from a single photon.

A dye sensitized solar cell (DSC) with a solar power conversion efficiency of 8% at AM 1.5 was first reported by O'Regan and Grätzel in 1991 [9, 10]. This achievement was realized by using titanium dioxide nanoparticles abutted together to form a porous film which was coated with a layer of adsorbed dye . The dye was then filled with electrolyte . The historic DSC has five main components : a dye , a porous high surface area oxide (typically a 10 mm thick layer of TiO_2 nanocrystals), a collector electrode (fluorine doped tin oxide), a redox couple (usually I^-/I_3^-) and a regeneration electrode (platinum) as shown in Fig. 30 . The advantages of TiO_2 are : low cost, availability , non-toxic and biocompatible .

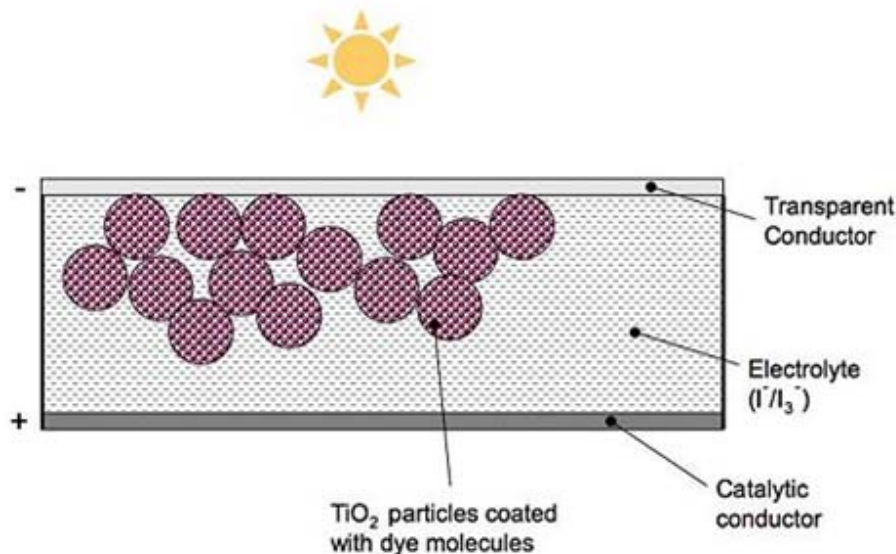


Fig .30 . Structure of a dye sensitized cell [9]

The working mechanism can be explained as follows : The dye absorbs the incident sunlight (not much light was absorbed in TiO_2 because this is a high band gap material) , generating electrons into TiO_2 . The dye is rapidly regenerated from its oxidized state by electron transfer from I^- . The photoinjected electrons diffuse to the back contact (Fluorine doped tin oxide electrode) and the regenerative cycle is completed by recycling tri-iodide I_3^- at the platinum electrode to return it back to iodide I^-).

In this type of device, photogenerated electrons travel to the electrode by hopping and there are thousands of hopping taking place which could increase the recombination rate , reducing the photocurrent. In order to reduce the hopping frequency, a direct path for electrons through for example nanowires or nanotubes may be beneficial .

Figure 31 illustrates another type of dye sensitized solar cell where TiO_2 is substituted with ZnO nanowires .

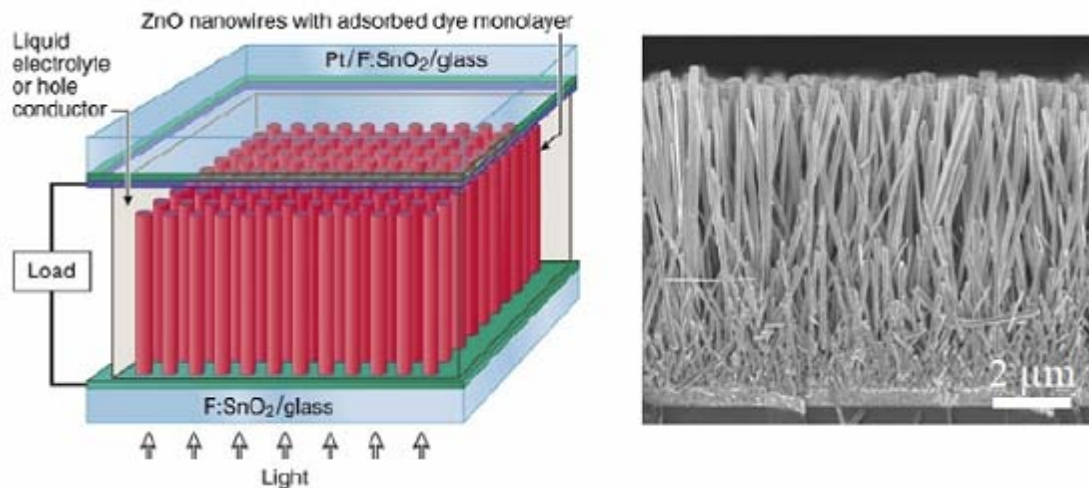


Fig. 31. Another type of dye sensitized cell where ZnO nanowires are employed [11] .

In this dye sensitized solar cell, ZnO nanowires which is the wide band gap semiconductor acting as an electron acceptor were grown vertically on a glass substrate from an aqueous solution of methanamine and zinc nitrate at a temperature at 95 C . CdSe quantum dots having quantum confinement effects are absorbed on ZnO nanowires as the sensitizer to convert light into the electrical current . CdSe quantum dots (nanometers in sizes) were synthesized

separately and attached to the surface of ZnO for form a photosensitized anode . A space of 25 μm was formed between the platinized transparent conducting oxide photocathode and the nanowire photoanode . The space was then filled with electrolyte which contains I_3^-/I^- .

Another type of advanced film solar cell is the organic solar cell which has been developed by Konarka . The materials are carbon-based polymers which are dissolved in solvents for coating. The advantages of this type of solar cell is non toxic materials, high speed roll-to-roll process, which could potentially lead to low cost solar cells . A roll-to roll coating system and an organic solar cell on a flexible substrate are shown in Fig. 32 [12].

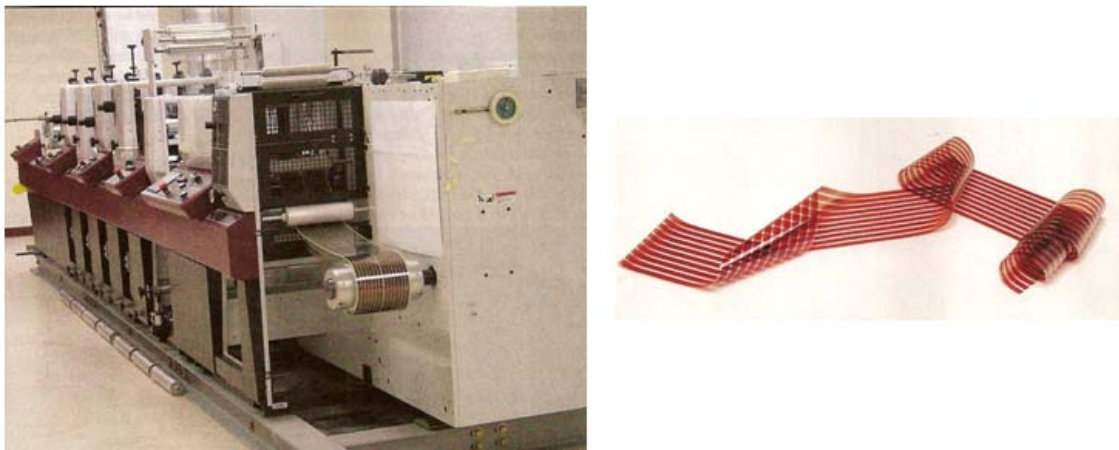


Fig. 32. Structure of an organic solar cell [Source : Konarka Inc.]

As shown in Fig. 33 , efficiencies of different types of solar cells have increased significantly over a period of nearly 30 years . The champion of all is the three terminal GaAs- based multi-junction concentrator with a conversion efficiency of 37.9% which was demonstrated by SpectroLab in 2005 . Crystalline silicon of Generation I had an efficiency as high as 24.7% , followed by polysilicon and CIGS, CdTe thin films of Generation II with efficiencies in the range of 15-20 % . Amorphous silicon had an efficiency of 12% , dye sensitized cell of 11% and organic cell of 5% . All the numbers quoted above are laboratory efficiencies . We can expect a reduction of 35-40% for module efficiencies, as can be supported by the data in Fig. 34. It should be noted in Fig. 28 that multi-junction concentrators have reached an efficiency of 40% , but the manufacturing cost therefore the system cost is also high . As a rule of thumb, for every 1% increase in efficiency , the cost is increased by 5 – 10 cents , provided that all other cost factors being equal (warranty, long-term depreciation etc...) . As an example,

for a cell having an efficiency of 7% with a cost of $\$0.5/W_p$, the cost will then be $\$1.3/W_p$ for a cell with an efficiency of 13%, that is $(\$0.5 + (13 - 7) \times \$0.1 = \$1.3)$.

Cost the the PV system is the sum of the cost of the PV module and the installation cost. Currently cost of a single crystalline silicon system is in the range of $\$6-8/W_p$ of which $\$3- \$4/W_p$ is the cost of PV module. Of all the solar cells in Figs 28 and 29, CdTe have a good chance to meet the $\$1.0/W_p$ goal of US Department of Energy in a couple of years. At present, production cost of CdTe module is $\$0.83-0.90/W_p$. As a reference, cost of amorphous silicon module is still in the range of $\$1.8- 2.2/W_p$.

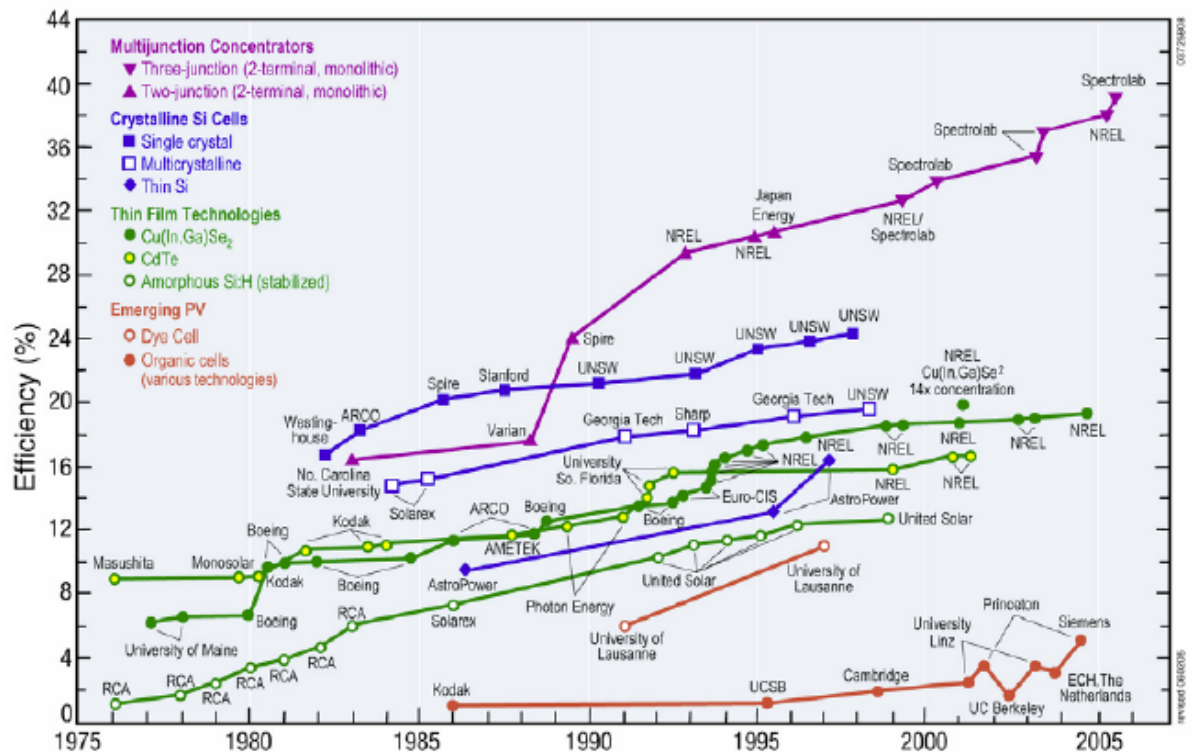


Fig 33. Improvements of solar cell efficiencies from 1976-2004 (NREL, Department of Energy)

	<u>Modules</u>	<u>Lab</u>
Multicrystalline or polycrystalline silicon	12 - 15%	20.3%
Monocrystalline silicon	14 - 16%	21.6%
High performance monocrystalline silicon	16 - 18%	24.7%
Amorphous silicon (multijunction)	6 - 8%	13.2%
Cadmium Telluride (CdTe) thin film	8 - 10%	16.5%
Copper-Indium-Gallium-Selenium (CIGS)	9 - 11%	19.5%
Triple-junction (GaInP/GaAs/Ge) cell (236 suns)	-	39.0%

Fig. 34. Module efficiency of different PV solar (BP Solar) .

9. Lowering the cost of PV solar electricity

Experience has shown that cost of the PV cells is inversely proportional to the manufacturing capacity , as shown in Fig . 35. This data serves as a supplement to the “80% learning curve” in Surek’s article which states that a 20% reduction in module price in doubling the production level. .

With that in mind, many companies are working on the in-line systems to develop their solar cells . Two major manufacturing processes are : PV factory and roll-to-roll . An example of the PV factory is the commercially available NanoFab of Applied Materials shown in Fig. 36. The factory has the following capacity :

- Turn key, glass in- module out ,
- Modules on a glass sheet of 2.2 m (width) x 2.6 m (length) and 3 mm thick; throughput : 22 sheets/ hour ,
- Module conversion efficiency of 6% (AM 1)
- Manufacturing cost of US\$1.30/ W_p (based on US labor) .

(Source : Applied Materials)

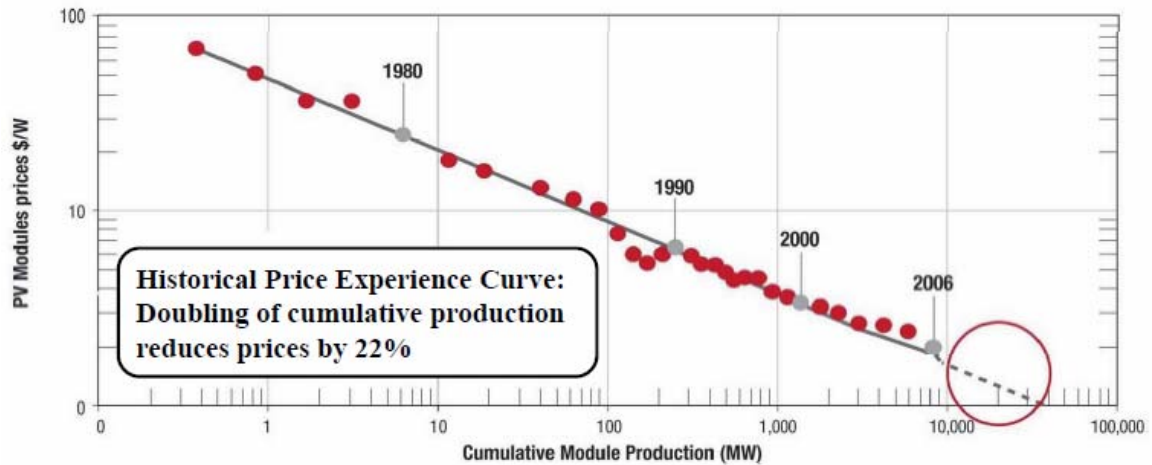


Fig. 35. The 20% learning curve (Sources : EU Joint Research Centre- National Renewable Energy Laboratory)



Fig. 36. PV factory of amorphous silicon solar modules (Applied Materials)

Whereas Fig. 37 shows an example of the roll-to-roll system for manufacturing amorphous silicon solar modules (United Solar) .



Fig. 37. A roll-to-roll coating system [Source : United Solar] .

One of the challenges in the in-line coating is the in-line patterning . We had created monolithically in-line patterns of CIS cell both on glass and on stainless steel substrate in a system shown in Fig. 38 and patterned samples are shown in Fig. 39 .



Fig. 38. A system for in line coating and in-line patterning of CIS solar cells .



Fig. 39. In-line patterned samples .

9. Which PV solar cells could potentially meet the DOE goal of \$ 1.0/ W_p and beyond?

In the foreseeable future, silicon solar cells continue to dominate the market whereas CdTe thin film cells are perhaps the only one which can meet DOE 's goal of \$1.00/ W_p . In the "high risk, high reward" category dye sensitized nanocrystalline solar cells are potential candidate for a conversion efficiency of above 30% without concentrators, which will put PV solar in a competitive position in relation to fossil and nuclear power.

10. Remarks on the PV solar in Viet Nam

Over all, the module efficiency of crystalline/ polysilicon is 12-16%; that of CIGS and CdTe cells 10% and that of amorphous silicon being 6-8% (Fig. 34) . In the author's opinion , those numbers are good enough , and from the practical point of view, we should focus on the manufacturing engineering which is dealt directly with reproducibility , stability over a period of 20- 30 years , mass production and yield . Since balance of system (BOS) is a component of the total cost, reducing BOS cost and increasing capacity in manufacturing engineering will definitely help reduce the total cost of PV solar systems .

Now, how can we apply the success of PV technologies and solar business to Viet Nam ? .

Viet Nam has the following advantages :

- Many sunny days : Viet Nam has an average solar radiation of 5 kWh/m² /day which is more than that of Germany being about 3 kWh/m² /day as can be seen in Fig. 40.

The solar radiation varies from city to city and from month to month , peaks in July at the average radiation of 5- 6 kWh/m² /day (Fig. 41)

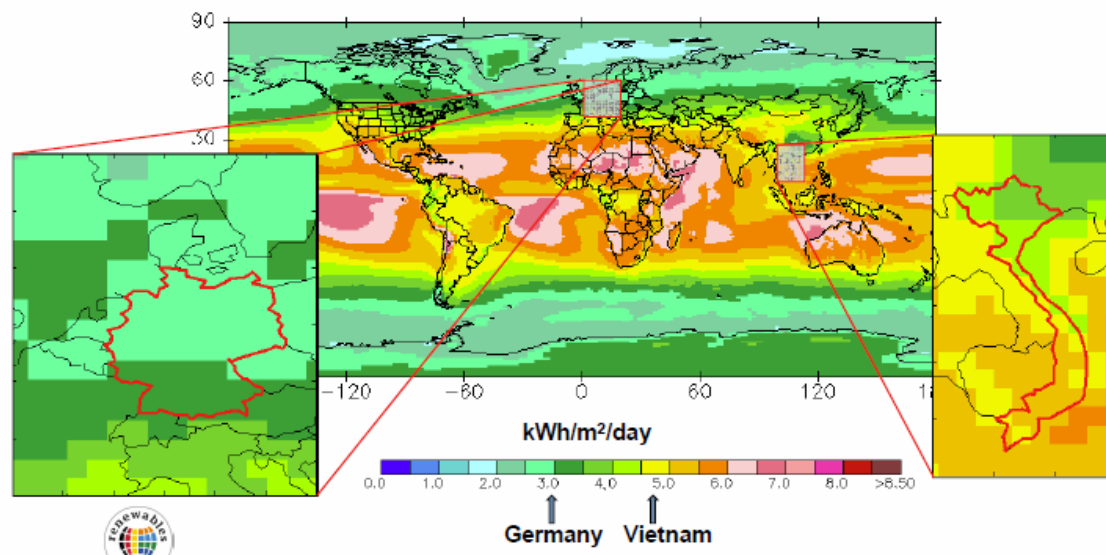


Fig. 40 . Average annual global solar insolation (Sources : German Federal Ministry of Economics and Technology and NASA)

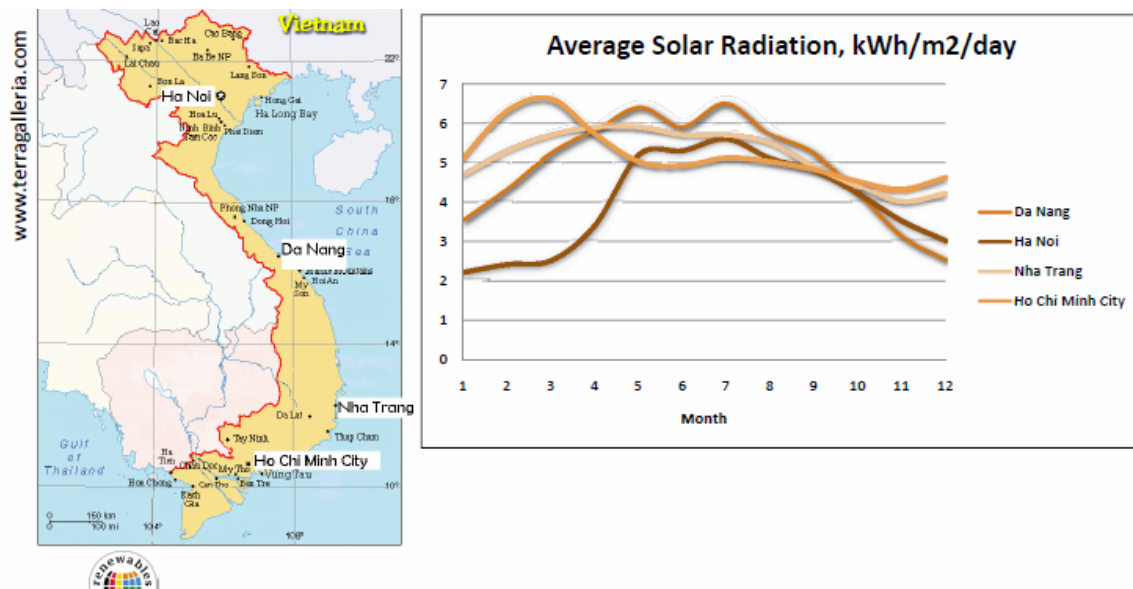


Fig.41 . Average solar radiation (kWh/m² /day) in different cities and different months in Viet Nam (Source: German Federal Ministry of Economics & Technology)

- Potentially high net electricity generation : Over a period of 28 years , the amount has jumped rapidly from 3 GWh in 1980 to approximately 60 GWh in 2008 (Fig. 42a) . Total electricity consumption per capita however remains at 1/10 of that in Germany (Fig. 42b) ,

indicating a good business potential and enormous domestic demand for solar electricity in Viet Nam

- Many remote areas
- Young work force and low labor cost
- Low SG &A (sales, general & administration , taxes) .
- Last but not least, a stepping stone building towards the future semiconductor industry in Viet Nam.

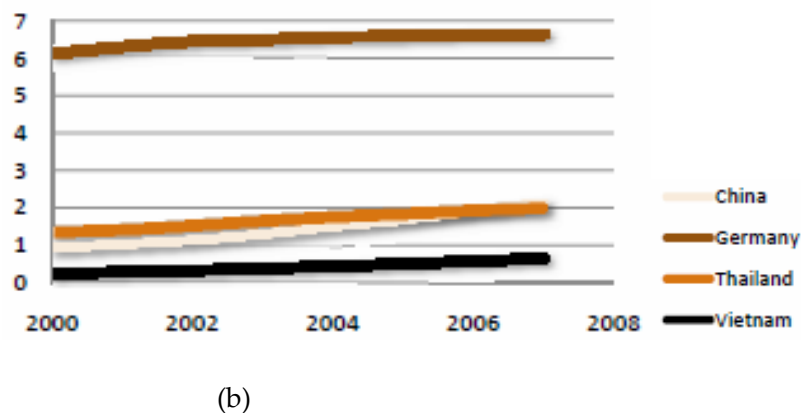
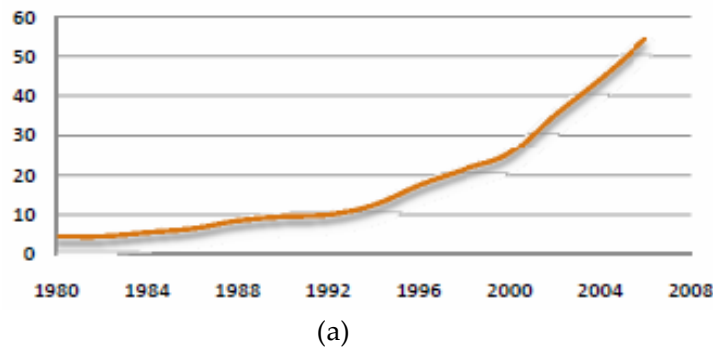


Fig. 42 . Electricity use in Viet Nam : (a) Total electricity net generation in Viet Nam (GWh); (b) Total electricity net consumption per capita (MWh/capita) (Source: German Federal Ministry of Economics and Technology)

In the initial stage , it is recommended that Viet Nam starts with crystalline silicon and polysilicon solar cells to build module assembly plants, the manufacturing engineering and the infrastructure since these materials are well known and silicon based solar cells occupy about 90% of the total market of solar modules . The next step will be thin film solar cells of Generation 2 and dye sensitized solar cell of Generation 3 . Since nanostructures are potentially used in many cell structure, working on solar cells will prepare those who work in the field with knowledge in nanotechnology, device

performance , circuit simulation and material coating and characterization. Those are the backbone for the development semiconductor technology in the future.
The three phases in the development of a PV solar industry in Viet Nam can be tentatively illustrated as in Fig. 43 .

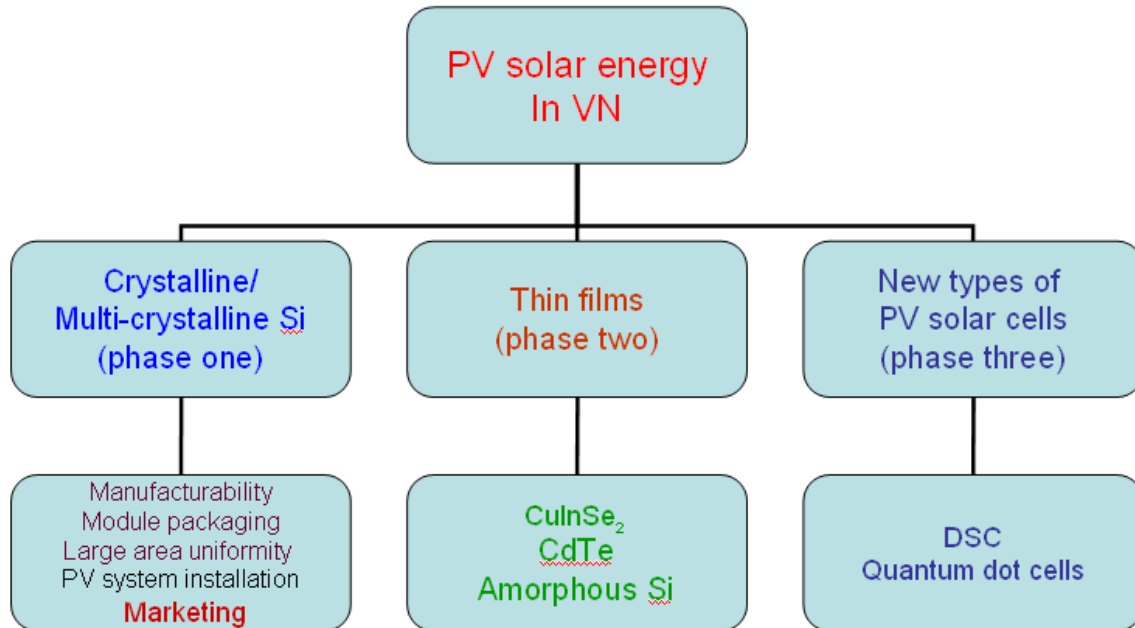


Fig. 43 . Three manufacturing phases of PV solar program in Viet Nam

The industry can focus on phase one whereas universities/ colleges will do R&D for phase two and phase three . In order to meet the \$0.4 /W_p and from the technical challenges and other potential applications of nanotechnology in medicine , nanosensors, nanoelectronics and battery , dye sensitized solar cells is be the subject of interest that the research institutions should focus their efforts on . One can fabricate nanowires, nanotubes and quantum dots, using the less expensive techniques such as chemical bath deposition and chemical vapor deposition. In doing so, one is able to build the foundation for developing nanotechnology in the future. “There’s Plenty of Room at the Bottom” as Professor Richard P. Feynman, the Nobel laureate in Physics and the “father of nanotechnology” said in his famous talk to the American Physical Society on December 29, 1959 [14] . There is “plenty of room” for different feature sizes for various practical applications! . Collaboration among industry , university and government as shown in the diagram in Fig. 44 is critical for the success of the industry . The government will take a lead in forming renewable energy policies, green energy initiatives and publicly subsidizing PV villages , PV water pumping units and PV water filtered systems .

The challenges here are : reducing cost and/or enhancing the conversion efficiency.

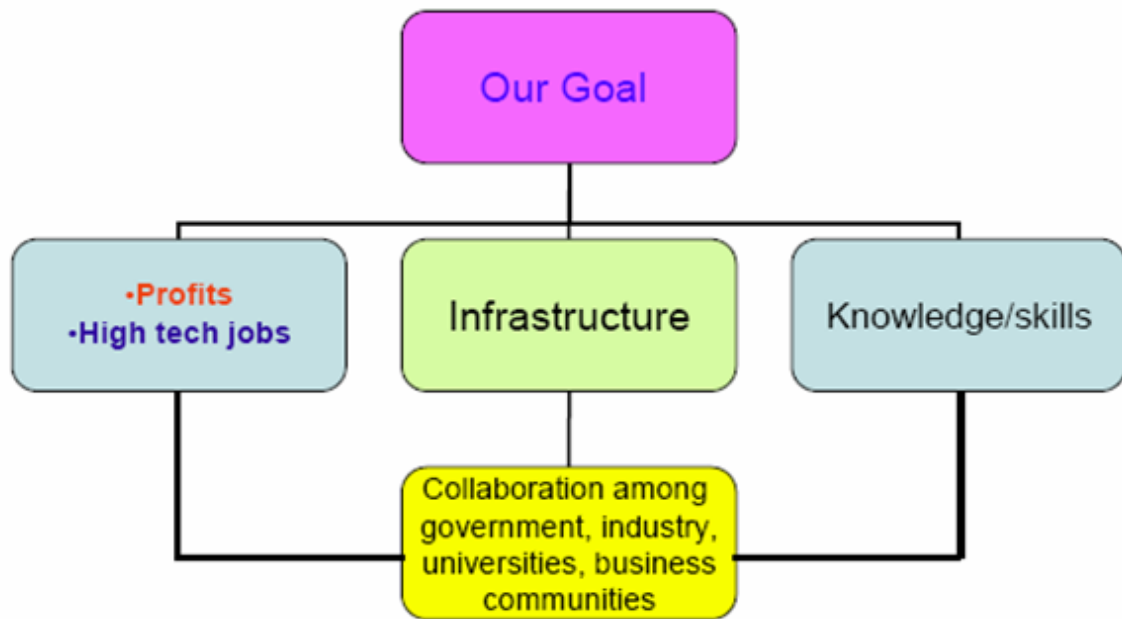


Fig. 44 Steps in building the PV solar industry in Viet Nam.

Many components required in making PV solar can very well constitute the infrastructure for thin films and future semiconductor electronics as shown in Fig. 45. In short, PV technologies will be used as a stepping stone for Viet Nam to move into other “high tech” applications in the future. Thin films, nanotechnology, device physics, manufacturing engineering and many others will put Viet Nam in a good position in establishing a knowledge economy. “There’s plenty of rooms” for filing patents in many areas of science and technology.

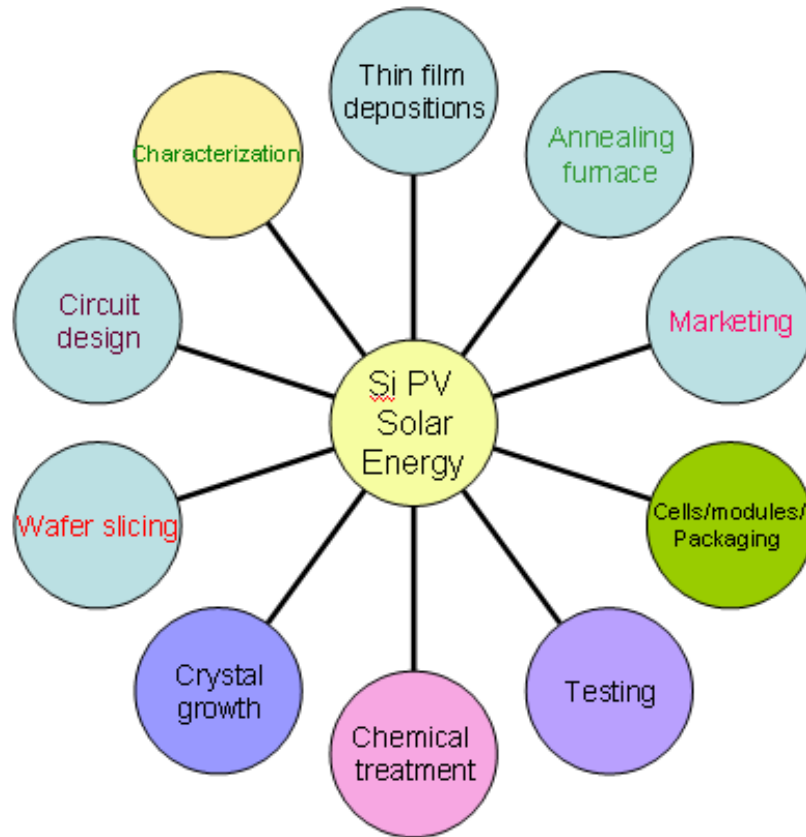


Fig. 45. Main components in making PV solar modules

And the applications are many ! (Fig. 46)

Potential markets could be : building integrated photovoltaics (BIPV), grid PV solar systems, solar power , especially for PV villages , PV water pumping units and PV solar powered water filtration systems .

- In the PV villages:

With PV centralized battery charging and telecommunications , mobile phones computers and internet can be used, which enhances the knowledge of villagers in health, information and study .

- For the water filtration :

There are several problems facing many rural towns and villages in Viet Nam: . It has been reported that water in Viet Nam, particularly in the North has been contaminated with arsenic, a highly poisonous semi-metal element which has been used in insecticides and animal feed . This material can cause partial paralysis, blindness and cancers in kidney, bladder , liver and prostate. Lacking access to the electricity grid because of a high cost in bringing electricity to these locations. As an alternative, the villagers employ diesel engines and powered motors for water delivery, which are expensive, noisy and unsafe. Many people have no access to safe drinking water ,

which causes a serious health hazard and the risk of water –borne diseases . Furthermore, rain and surface water from rivers, lakes, ponds and reservoirs are generally contaminated with bacteria, waste materials from industry, various types of chemicals from the war ; whereas the ground water has high mineral content and is full with arsenic, chloride, sulfate, nitrate, iron, magnesium , nitrate or detergent contamination from sewage , just to name a few. As a result, water of good quality is in urgent need. In addition, people in the remote islands and/or by the sea need drinking water and one of the way to obtain that kind of clean water is from the desalination process which is not available in many locations. *Good water brings about a happy life. In the countryside, electrification is a symbol of wealth and health .*

- Water pumping units: One pumping unit with 0.5 kW PV solar array can provide 1,000 gallons of water / a day with 100 feet lift . Quality of the deep water is good and water can be stored in tanks for portable uses .

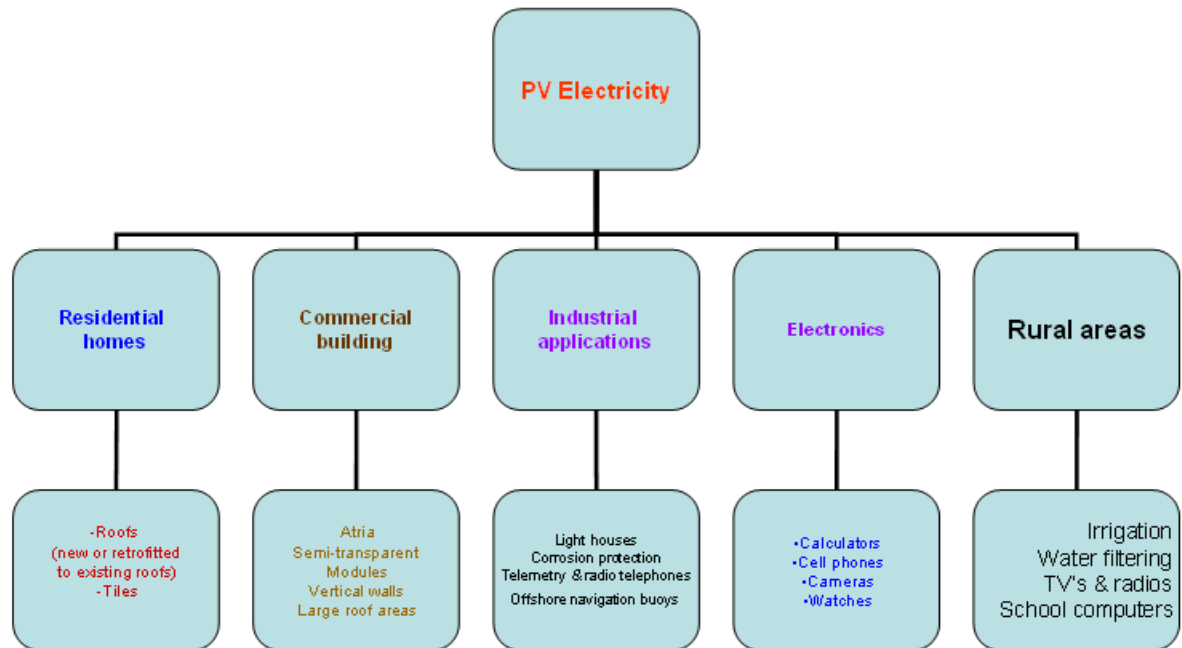


Fig. 46. Applications of PV electricity in Viet Nam .

11. Conclusions

Over the years, significant progress has been made on improving the cell/ module efficiency , resulting in a reduction in cost from US\$70.00/ W_p in 1976 to US\$3.50/ W_p in 2003 . Taking the 80% learning curve [Surek, 2005) into consideration , by increasing production rate and with the incorporation of new technologies , a cost figure merit of US\$1.00/ W_p is achievable. As it stands now, CdTe solar cells have potential to reach that goal in a couple of years. This

could be the limit for cells of Generation I and Generation II due to the Shockley- Queisser limit [13] .Beyond this milestone , one has to look into PV solar cells of Generation III such as dye-sensitized solar cells which is a “high risk , high reward” type of devices . Once a cost figure of merit of US\$0.40/ W_p is reached , PV solar electricity will occupy a great share in providing energy to the world. As a late comer , Viet Nam can learn many mistakes from the pioneers in the field and therefore can adjust the strategy in research and manufacturing to make solar electricity a successful business in the years to come .

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