CHAPTER II

THEORETICAL AND RELATED LITERATURE

Solar PV Modules

PV Basics

PV is a technology whereby sunshine is directly converted into electricity.

Solar Power is the most reliable source of electricity in the world today. Photovoltaic modules generate electricity when they expose to sunlight - directly or indirectly [2].

Photovoltaic means electricity from light. Photovoltaic process converts free solar energy – the most abundant energy source on the planet – directly into electricity. The actual creation of usable electrical current in a photovoltaic or solar cell takes place at the atomic level. Solar cells are made up of solar grade silicon that is treated with positively and negatively charged semi-conductors, Phosphorous and Boron; this process is called "doping". When light energy (so called "photon") strikes the face of the cells, it excites the electrons within the cell. This flow of electrons (so called "current") is what called the PV effect.

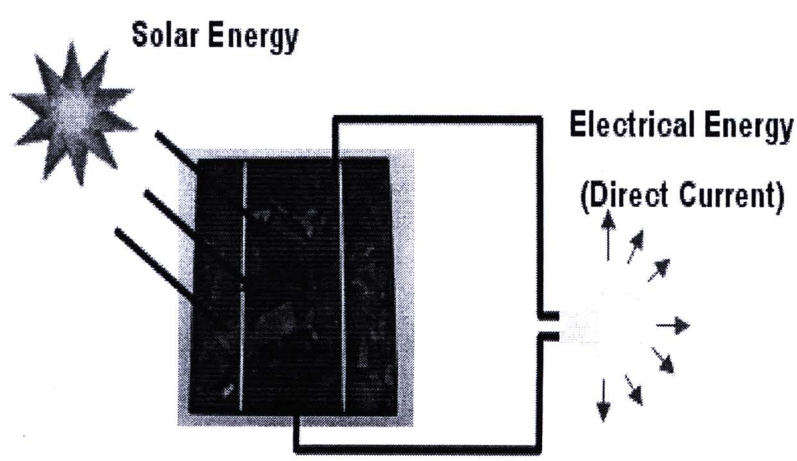


Figure 1 Solar Energy can be transformed into Electricity

The electrical output from a single solar cell is small. So multiple cells are connected together and encapsulated (usually behind glass) to form a "module" (sometimes referred to as "panel"). A number of individual PV modules connected together is called "PV array" and gives the required power with suitable current and voltage output.

PV panel has no moving parts and as a result requires minimal maintenance. It generates electricity without producing emission of greenhouse or any other gases, and its operation is virtually silent.

Solar cell

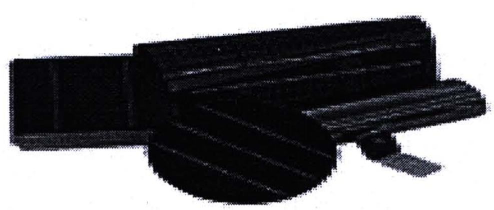


Figure 2 Various Types of PV Cells and Modules

A solar cell or photovoltaic cell is a device that converts light into electrical energy. Sometimes the term solar cell is reserved for devices specifically capture energy from sunlight, while the term photovoltaic cell is use when the light source is unspecified. Fundamentally, the device needs to fulfill only two functions: photo-generation of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity.

Solar cells can be according to their crystalline structure divided into four categories. Following are brief descriptions and some features of each type.

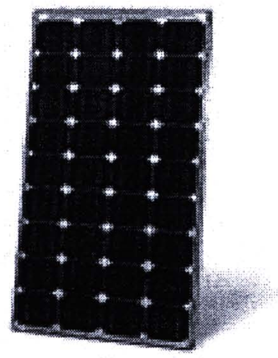


Figure 3 Mono- or Single-crystalline PV Module

1. Mono (or single) crystalline silicon cells made from very pure mono-crystalline silicon and have a single and continuous crystal lattice structure with almost no defect or impurities. The principal advantage is their high efficiencies, typically around 17%. The manufacturing process required to produce mono crystalline is complicated and has higher cost than other technologies. Different manufacturing methods are used, one depending largely upon the Czochralski method of growing, or pulling perfect crystal, another is based on the string ribbon technique where two high temperature strings are pulled vertically through a shallow silicon melt and the molten silicon spans and freezes between the strings. Another technique is so called EFG (Edge defined Film Growth) where the cells are cut from a pseudo-square octagon.

Figure 4 Multi- or Poly-Crystalline PV Module

2. Multi crystalline cells are produced using numerous grain of mono crystalline silicon. In the manufacturing process, molten polycrystalline is cast into ingots, which are square or rectangular in shape. These ingots are then cut into very thin wafers and assembled into complete cells. Multicrystalline are cheaper to produce than mono crystalline ones, due to less complicate manufacturing process. However they are tended to be slightly less efficient, with average efficiencies of around 1%.

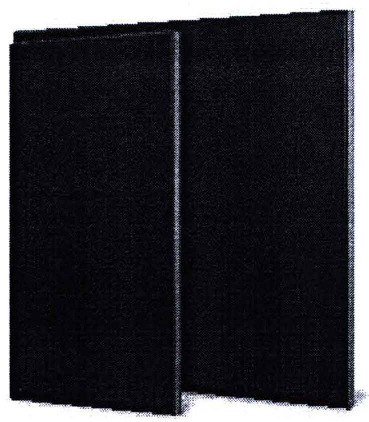


Figure 5 Amorphous Silicon PV Modules

3. Amorphous silicon cells are composed of silicon atoms in thin homogeneous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cell can be thinner. For this reason, amorphous silicon is known as thin-film silicon PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible. Amorphous cells have typical efficiencies of around 6%, are cheaper to produce and have lower temperature behavior under the hot operating condition compared to crystalline cells. High temperature will reduce operating voltage and therefore photovoltaic performance. A-Si modules and also other thin-film types are most suitable for hot climate and diffused irradiance conditions. A-Si thin-film can in short- and log-term be upgraded to much higher efficiency through the novel nano-technology already available.

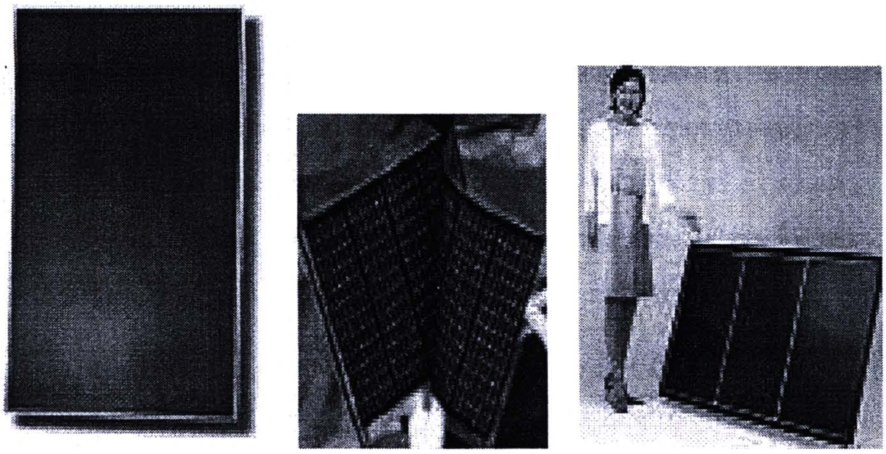


Figure 6 CdTe and CIGS PV Modules

4. Compound thin-film PV cells. A number of other promising materials such as Copper Indium Diselenide (CIS), Copper Indium Gallium Diselenide (CIGS) and Cadmium Telluride (CdTe) are now being used as PV modules. The attraction of these technologies is that they can be manufactured by relatively inexpensive industrial process, certainly in comparison to crystalline silicon technologies, yet they offer higher module efficiency comparing to amorphous silicon.

5. Spectrum Response of the PV Modules

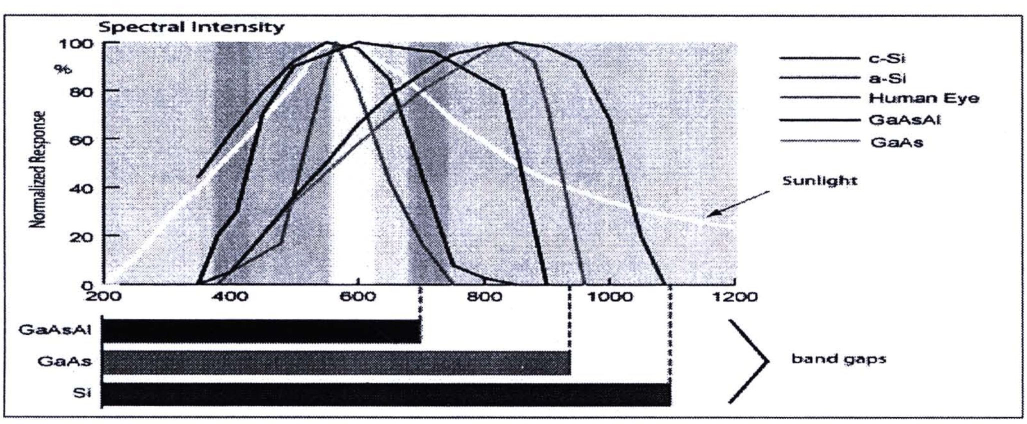


Figure 7 Response to Light Spectrum of different PV Modules

Source: Green Rhino Energy

PV modules do not all the solar energy within the visible region to electricity as they respond to different wavelengths. or having different band-gap. For example, crystalline silicon PV modules transform light to electricity well between 500-1,000 nm while amorphous silicon PV modules at around 400-700 nm. In-house TCO glass intended for using as the superstrate of a-Si PV module in this study shall therefore have optical transmission of 80% between 400-700 nm regions.

PV System Applications

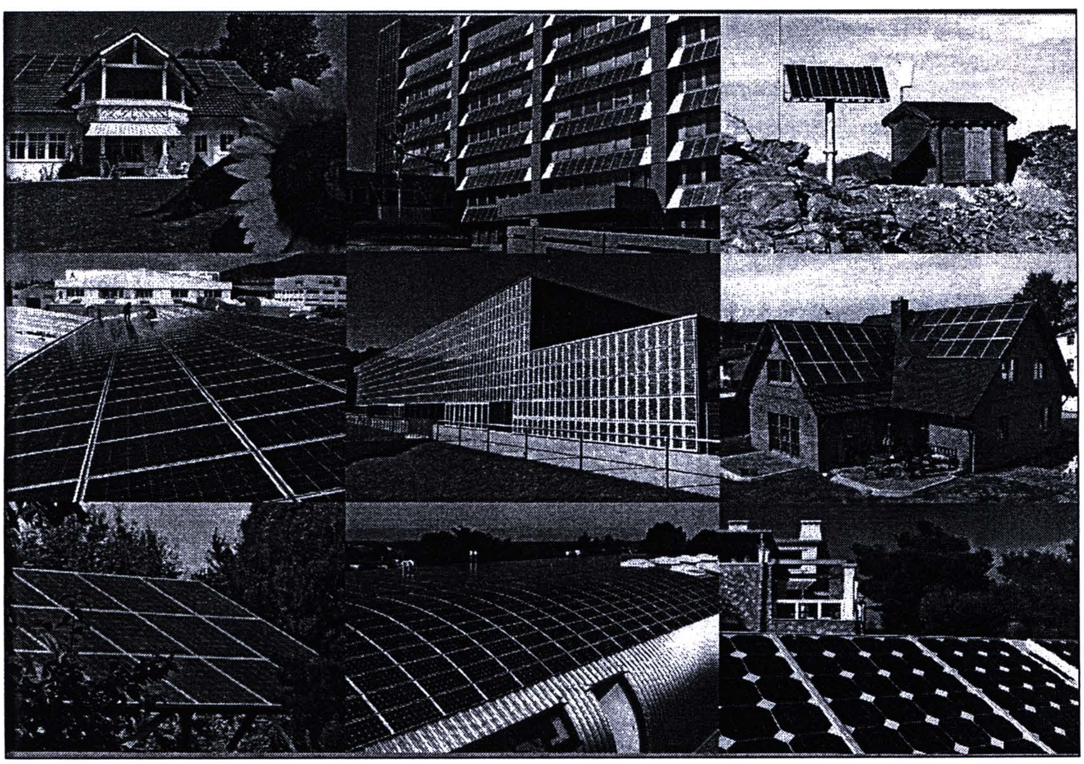


Figure 8 Applications of PV Modules

Solar cells are often electrically connected and encapsulated as a module. PV modules often have a sheet of glass on the front (sun up) side, allowing the light to pass through while protecting the semi-conductor wafers or layers from the external environments (rain, hail, moisture etc.).

The solar cell is the basic unit in a PV system. An individual solar cell can vary in size from about 10 centimeters to 20 centimeters across and typically produce 1 to 4 watts power, insufficient for the majority of applications. We can increase the power by connecting cells together to form larger unit called Modules. The cells are welded in a serial to a string of several solar cells, for a standard application, up to 36 or 72 cells are connected in series. Thin-film materials like amorphous silicon, CIS, CIGS and Cadmium Telluride can be made directly into modules through PECVD process or other sputtering (PVD) methods. The cell materials are being deposited on the substrate, either glass, polyamide or stainless steel or interconnected to form a module by laser scribing equipment.

Modules are then inter-connected in series or parallel, or both, to create an array with desired peak dc voltage and current. The size of an array depends on several factors, such as the amount of sunlight available in a particular location and the needs of consumers. The number of the modules in the individual string determines the system voltage and the number of parallel strings determines total current. A string is dependent on the voltage input limit of the inverter. Resistance losses in the wires rendered by the amount of current flows, good PV system should be designed as higher voltage and lower current to minimize the cable cost and losses [3].

The power output of a solar array is given in watts or kilowatts. To calculate the typical energy needs of the application, a measurement normally done in watt-hours, kilowatt-hours per day or per year.

PV technology is providing pollution and noise –free electricity with many impressive examples already in operation. Approx. 75-80% (status 2007) of the main applications of all PV systems is grid-connection to the local electricity network. While the rest are off-grid or stand-alone PV systems mostly installed in the remote areas.

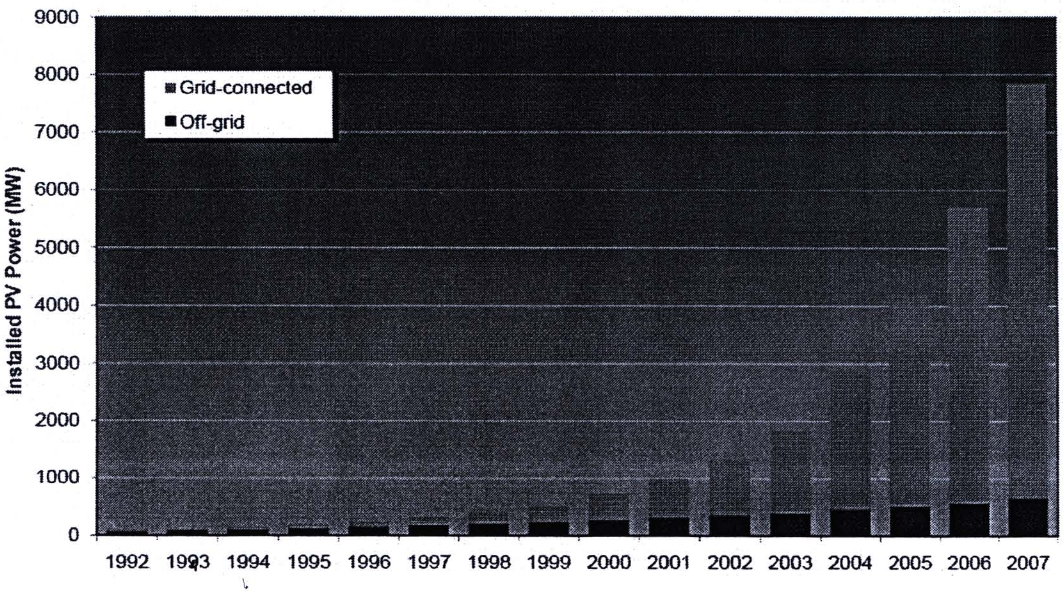


Figure 9 Installations and Applications of PV Modules in the World

Grid-connected PV systems are often integrated into buildings so called BIPV or on the roof or ground-based. This means that during the day, the electricity energy generated by the PV system can be used immediately or can be sold to of the electricity supply companies. In the evening, when the solar system is unable to provide the electricity required, power is provided by normal electricity network. In effect, the grid is acting as energy storage system, which means the PV system does not need to include battery storage.

Grid-connected PV system offers consumers both economic and environmental advantages. Where the distribution line from utility is available, consumers can use a grid-connected P system to sell a portion of or the whole power to the utility at a favorable feed-in tariff rates (so called "adder" in Thailand) during the day while using utility-generated power at night or on cloudy day at normal electricity rate.

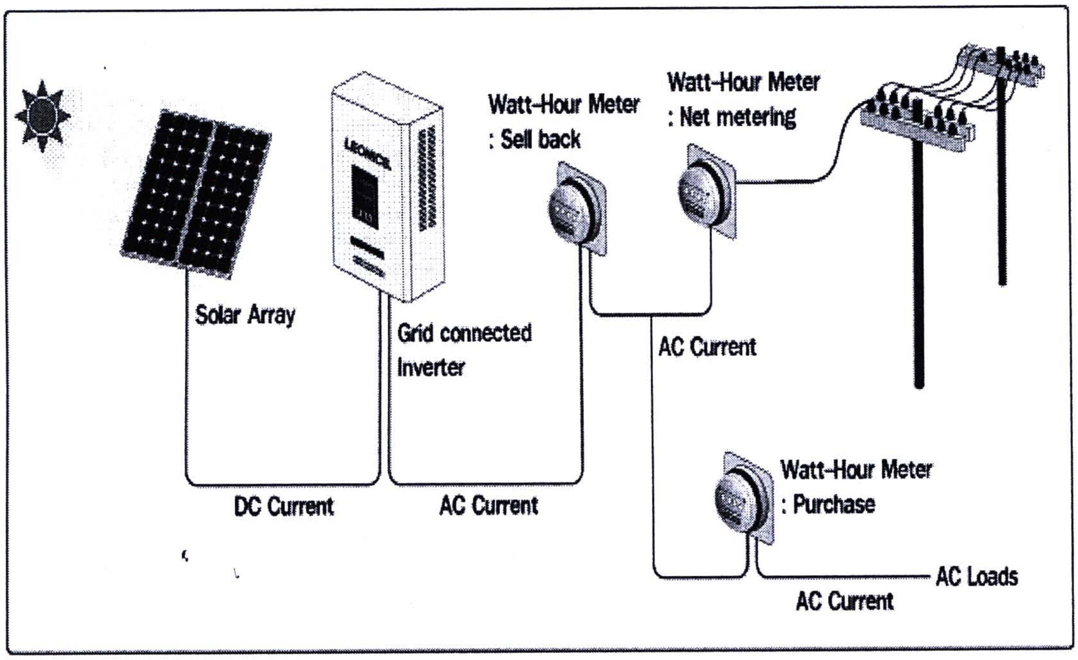


Figure 10 Schematic Diagram of Grid-connected PV System

Off-grid PV system sometimes called stand-alone system, is designed to provide electricity to a home or business without drawing on supplemental power from the electrical utility. A basic of off-grid system consists of solar modules, a battery bank, a charge controller that manage battery charging, an inverter/charger that is the intelligent center of the system, and a generator or wind turbine as an optional source of back-up. During the day time, the solar modules generate power to charge batteries and provide electricity. At night, the inverter/charger automatically runs the electrical equipment from battery bank. The generator provides additional back-up on battery charging capability for extended period of cloudy weather. The inverter/charger can automatically start the generator and initiate a recharge cycle when the battery bank is depleted, or load is too large for the battery to support independently.

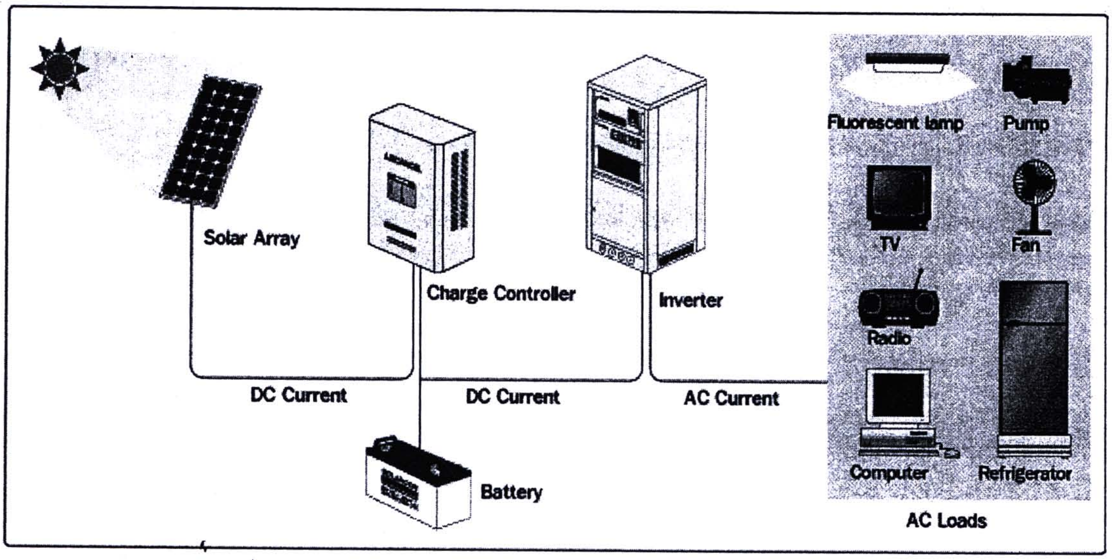


Figure 11 Schematic Diagram of Off-grid PV System

The photovoltaic array is normally exposed to sunlight. Depending on design, the interconnecting wires may also be exposed. All exposed wiring must also meet electrical codes for outdoor application, notably exposure to UV radiation. The electrical power produced by the photovoltaic array has some unique characteristics which required special attention. It is direct current and the source is limited by current. Some installers may not be familiar with direct current and the system will require special components for switching and isolation.

Demand of Solar Modules and Technology Shift [4]

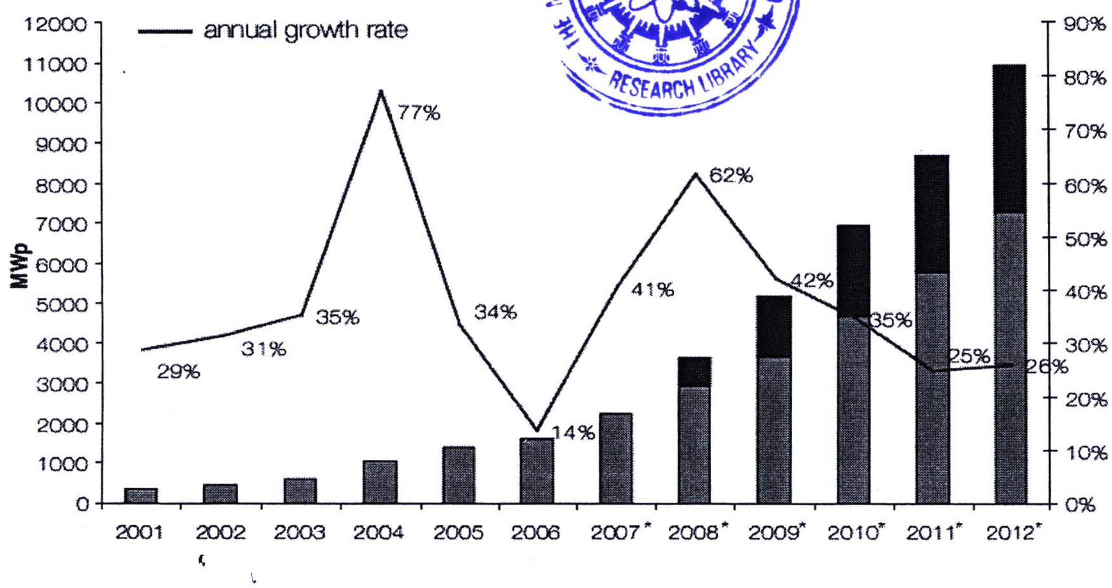


Figure 12 Demand of PV Modules during 2001-2012

Recorded oil price and speculations on whether the oil price would peak at above $100 in 2010 as well as the forecast that the oil will be depleted within the next 40 years. Such development has shifted the focus from oil to more abundant fossil energy resources like gas and coal. The gas crisis in Europe in 2006 as well as the global warming situation due to too high emission of CO_2 and other greenhouse gases to atmosphere helps influencing the diversification of energy sources to also including renewable energy and photovoltaic.

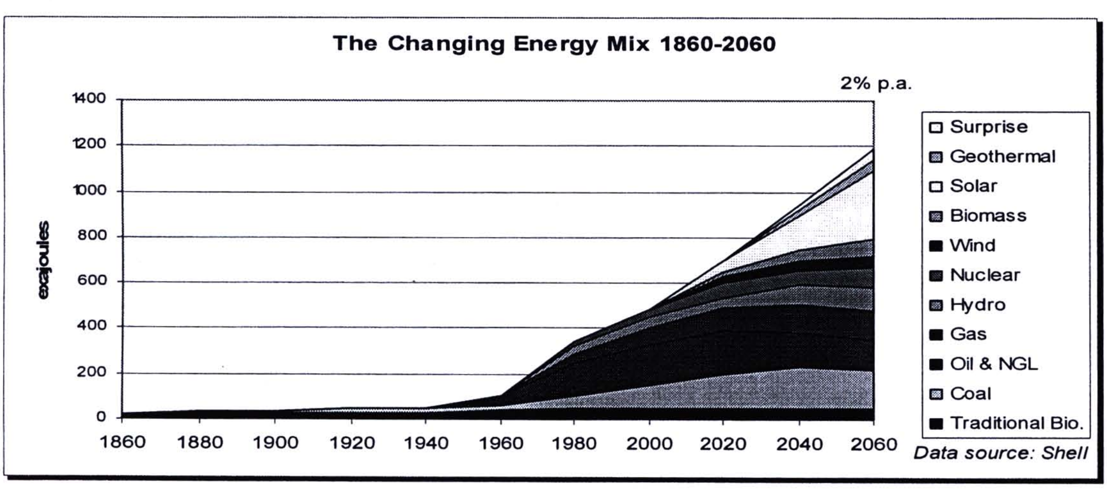


Figure 13 Future Energy Shift – Solar Energy will Play Major Role

Photovoltaic is a key technology option to realize such a shift. The current solar cell technologies are well established and provide a reliable product, with sufficient efficiency and energy output for at least 20 years of life time. During the past 15 years (1990-2005) the demand of PV cells has increased from 46.5 MWp in 1990 to 2,500 MWp in 2006. The growth of this industry has grown in average above 30% per year during the past 5 years. The solar power sector continues its rapid ascent. In volume terms, the sector is on the path to grow from 3.9 GW of cell/module production in 2007 to more than 7 GW in 2008, 14.7 GW in 2009 and at least 52 GW in 2012. This 60 percent plus annual growth is significant upside potential of the bulk silicon and thin-film production.

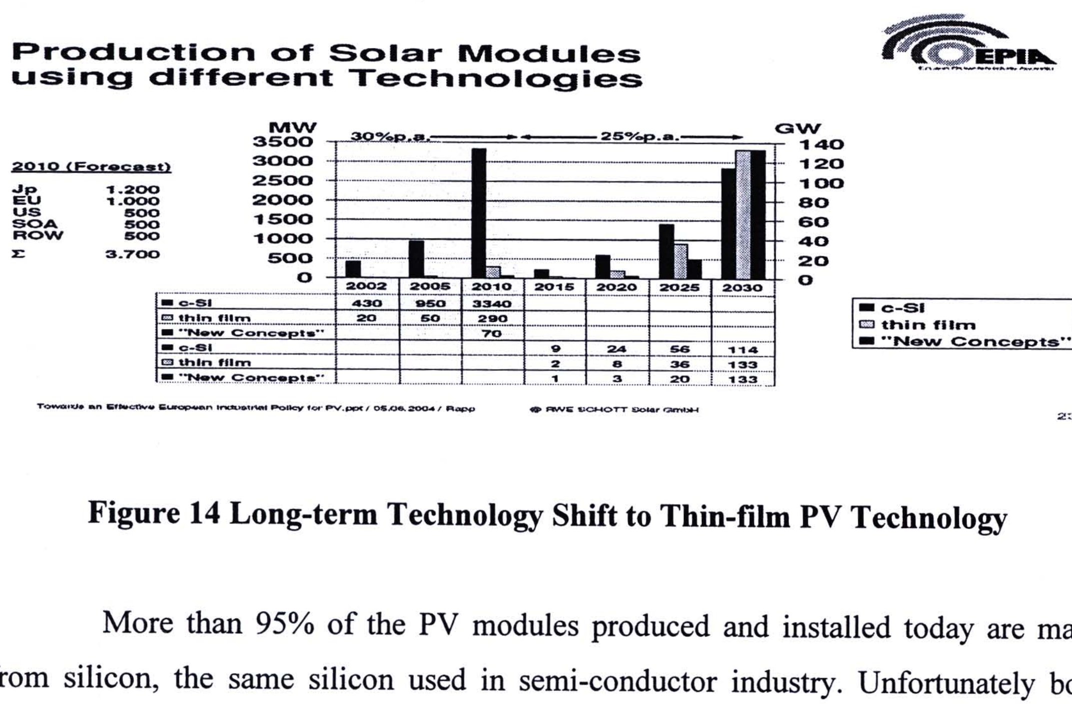


Figure 14 Long-term Technology Shift to Thin-film PV Technology

More than 95% of the PV modules produced and installed today are made from silicon, the same silicon used in semi-conductor industry. Unfortunately both semi-conductor and PV industry grows at the same pace and same period and pushes for higher demands for ultra-high purity silicon materials. Consequently the UHP-silicon materials become scarce and much more expensive. Many existing PV module manufacturers as well as the new investors are shifting their targets towards thin-film PV silicon technology which use much less silicon, cheaper to produce and has clear path for both efficiency as well as cost improvement in the near future. It is forecasted that thin-film silicon will account up to 10 % of the total market in 2010 and will then take at least one-third of the total PV market by year 2030.

Thin-film Silicon PV Modules

Why Thin-film Silicon?

As mentioned previously that 80% of all the PV modules manufactured are used for grid-connected system to sell the electricity to the electrical network at a favorable feed-in tariff which is reducing 7 percent every year. To be able to be competitive and achieving a lower investment coast of the system, cheaper PV modules is one of the key solutions. Due to the fact that thin-film silicon PV modules posses following advantages i.e.

1. Abundantly available raw materials
2. Low Silicon and energy consumption
3. 15-20% more energy yield kWh/kWp than c-Si, CIGS, CdTe
4. Better visual appearance
5. Wider ranges of applications including BIPV
6. Proven potential for higher efficiency towards 20%
7. Lowest cost and grid-parity compatibility
8. Possibility for flexible pv modules

With the main advantages described above, it is no doubt that thin-film silicon PV modules will within a decade take a major portion of the future PV modules market all over the world.

Thin-film Technologies Overview

The various thin-film technologies currently being developed reduce the amount or consumption of light absorbing materials required in creating solar cells. This can lead to reduced processing costs from that of bulk materials (in case of thin-film silicon) but also tends to increase energy conversion efficiency. Brief overview of various thin-films is described below.

1. CdTe

Cadmium telluride is an efficient light-absorbing material for thin-film solar cells. Compared to other thin-film materials, CdTe is easier to deposit and more suitable for large scale production. It has approx. 7-9 percent efficiency. The perception of the toxicity of CdTe is based on the toxicity of the elemental cadmium, a heavy metal that is a cumulative poison which may be banned by some counties.

2. CIGS

CIGS are multi-layered thin-film composites. The abbreviation stands for Indium Gallium Selenide. The best efficiency of GICS thin-film solar cell was 19.5% as of December 2005. However higher efficiencies up to around 30% can be obtained by using optics to concentrate the incident light. The uses of Gallium increases the band gap of the CIGS layer as compared to CIS thus increase the cell voltage. Due to relative availability of Gallium to Indium, Gallium is therefore added to replace as much Indium as possible. Approximately 70% of Indium currently produced is used by the booming flat-screen monitor industry and now rather limited and expensive. Selenium allows for better uniformity across the layer and so the number of recombination sites in the film are reduced which benefits the quantum efficiency and thus conversion efficiency.

3. CIS

The materials based on $CuInSe_2$ which have high optical absorption coefficients and versatile optical and electrical characteristics. CIS is the abbreviation for general chalcopyrite films of copper indium selenide ($CuInSe_2$), CIGS mentioned earlier is a variation of CIS. CIS can achieve 13.56% efficiency; their manufacturing costs at present are still high compared with a silicon solar cell.

4. GaAs

Gallium Arsenide is a multi-junction, high efficiency solar cells developed for special applications such as satellites and space exploration. GaAs cells consist of multiple thin-film produced molecular beam epitaxy, produced with rather complex process and are the most efficient solar cell to date, reaching a record high of 40.7% efficiency under solar concentration and laboratory conditions. In the production, GaAs triple-junction cells reach above 28.3% and they are the most expensive cells i.e. US$ 40 per square cm.

5. Dye-sensitized

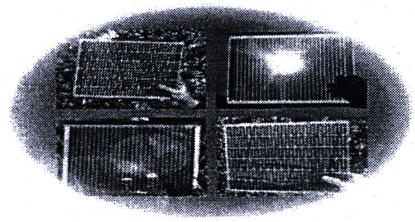


Figure 15 Dye-sensitized Cells

The dye-sensitized solar cell depends on a mesoporous layer of nanoparticulate Titanium Dioxide to greatly amplify the surface area i.e. required 200-300 m^2/gram of TiO_2 as compared to approximately 10 m^2/gram of flat single crystal. The photo-generated electrons from the light absorbing dye are passed on to the n-type TiO_2, and the holes are passed to an electrolyte on the other side of the dye.

This type of cells allows more flexible use of materials, and can be manufactured by screen-printing with the potential for lower processing costs but the dyes in these cells are suffer from degradation under heat and UV light, and the cell casing is difficult to hermetically seal due to the solvents used in the assembly. However, it is a popular emerging technology with some commercial impact forecasted within this decade.

6. **Thin-film Silicon**

Thin-film silicon cells are mainly deposited by typical Plasma Enhanced Chemical Vapor Deposition (PECVD) method using ultra high purity silane gas, hydrogen gas and other dopants. Depending on the deposition's parameters, this can yield:

6.1 Amorphous silicon (a-Si or a-Si:H)

6.2 Micro-crystalline silicon (mc-Si)

6.3 Nano-crystalline silicon (nc-Si or nc-Si:H)

These types of silicon cells present dangling and twisted bonds, which results in deep defects (energy levels in the band gap) as well as deformation of the valence and conduction bands (band tails). The solar cells made from these materials tend to have lower energy conversion efficiency than bulk silicon, but are also less expensive to produce. The quantum efficiency of thin film solar cells is also lower due to reduced number of collected charge carriers per incident photon.

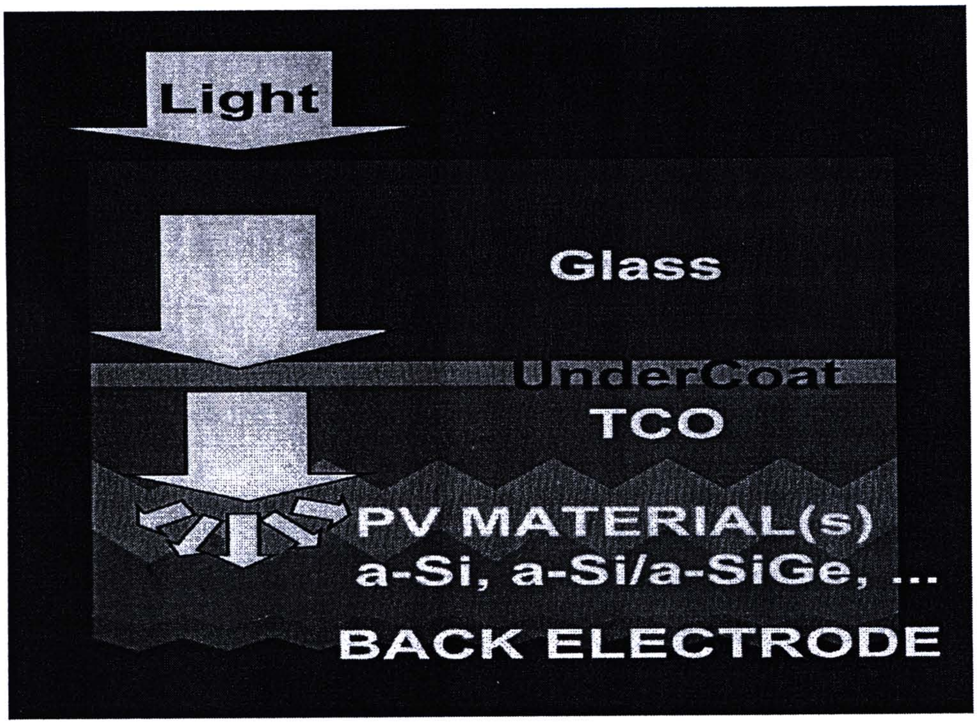


Figure 16 Structure of Thin-film a-Si PV Cell

Amorphous silicon (a-Si) has a higher band gap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. As micro- or nano-crystalline Si (mc- or nc-Si) has about the same band gap as c-Si, the mc- or nc-Si and a-Si can advantageously be combined in thin layers, creating a layered cell called a tandem cell. The top cell in a-Si absorbs the visible light and leaves the infrared part of the spectrum for the bottom cell in micro- or nano-crystalline Si.

Recently, solutions to overcome the limitations of thin-film silicon have been developed. Light trapping schemes where the incoming light is obliquely coupled into the silicon and the light traverses the film several times enhance the absorption of sunlight in the films. Thermal processing techniques enhance the crystallinity of the silicon and pacify electronic defects. The result is a new technology – **thin-film crystalline silicon on glass (CSG)** which is a solar devices represent a balance between the low-cost of thin-film silicon and the high efficiency of bulk silicon.

A silicon thin film technology is being developed for building-integrated photovoltaic (BIPV) in the form of semi-transparent solar cells which can be applied as window glazing. These cells function as window tinting while generating electricity.

7. Nano-crystalline solar cell, further development of thin-film silicon technology

These structures make use of some of the same thin-film light absorbing materials but are overlain as an extremely thin absorber on a supporting matrix of conductive polymer or mesoporous metal oxide having a very high surface area to increase internal reflections (and hence increase the probability of light absorption). Using nano-crystals allows one to design architectures on the length scale of nanometers. In particular, single-nanocrystal ('channel') devices, an array of single p-n junctions between the electrodes and separated by a period of about a diffusion length, represent a new architecture for solar cells and potentially high efficiency and with no light degradation.

Production Process of a-Si Thin-film PV Modules

In this section, glass-to-glass a-Si thin-film PV modules manufacturing process flow diagram and brief description as well as relevant photos of the equipment will be shown.

1. Process Flow Diagram

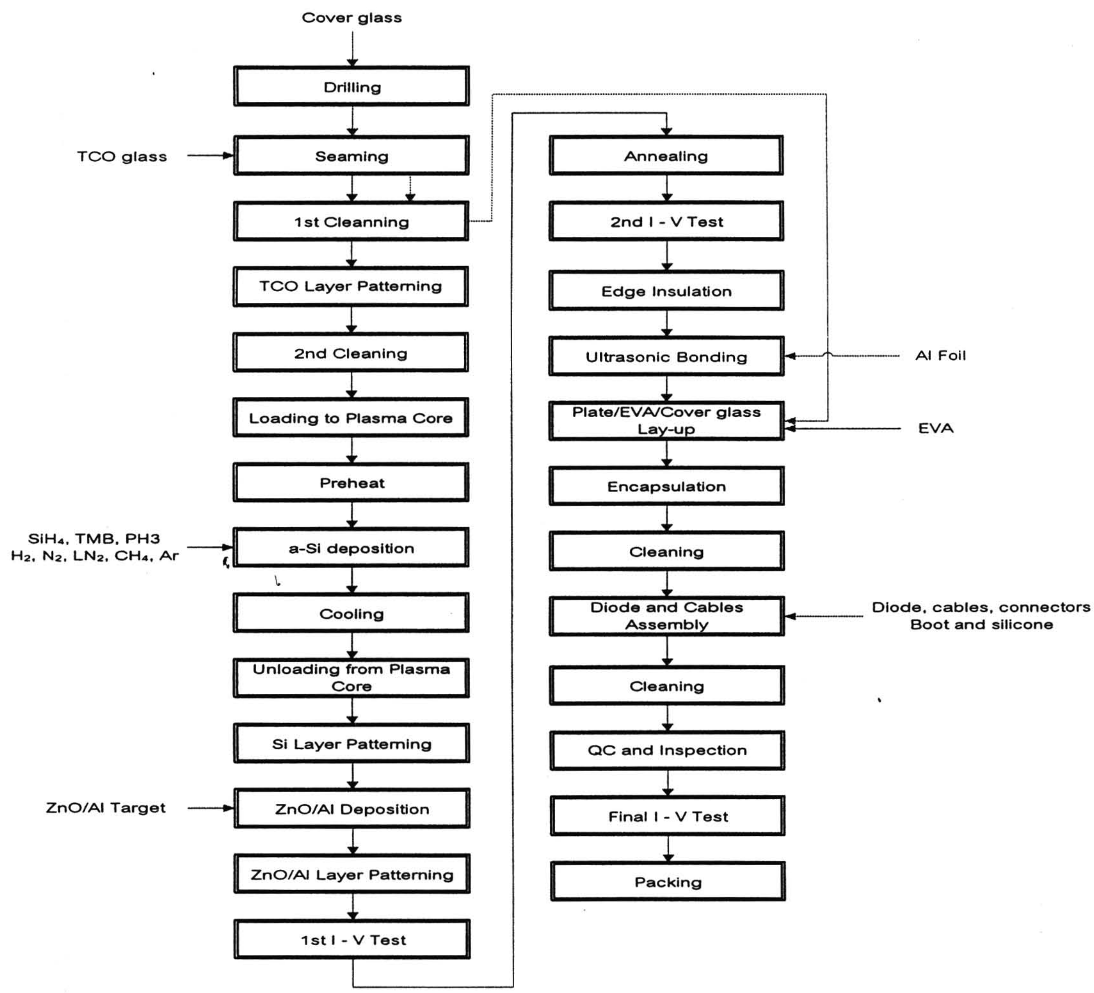


Figure 17 Process Steps of Thin-film a-Si PV Modules Production

In the present production process of thin-film a-Si PV modules, commercial TCO glass produced by and purchased from the float glass factories is used as raw material, while in the latter part of this study, using of TCO glass deposited in-housed will be discussed.

2. Production Process Description

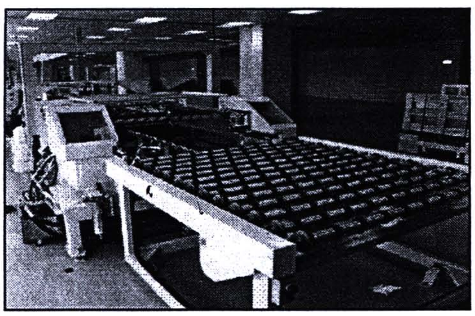
Thin-film a-Si PV modules can be manufactured by continuous-type process, cluster-type process or batch-type process depending on the process and equipment providers. In this study we will mainly concentrate on glass-to-glass thin-film a-Si PV modules production of batch-type process with the following process steps.

1. Glass preparation:

1.1 Seaming (edge smoothing) of the TCO glass substrate with double-edger.

1.2 Drilling of the cover glass, and

1.3 Cleaning of the TCO glass substrate and cover glass by glass washer.



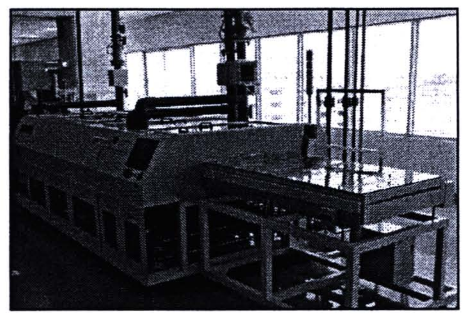


Figure 18 Glass Preparation Equipment

2. Patterning of P1 layer: the selective removal of conducting thin-film on the TCO glass substrate by scanning a focused infrared laser (wavelength 1,064 nm) beam. The laser scribing system is housed in an environmental controlled enclosure to maximize the performance of the equipment. After this process, the TCO glass will be cleaned again before being loaded into the plasma core box.

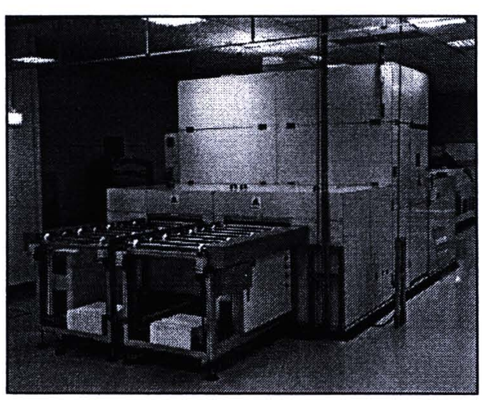


Figure 19 Infrared Laser Equipment

Figure 20 Pre-heat Oven

2.1 Pre-heating of a-Si substrates: the heating of the laser-patterned TCO glass substrates will be done in the a-Si pre-heater oven up to 200°C prior to the deposition of thin-film a-Si layers in the PECVD chamber.

2.2 Fabrication of a-Si layers: the primary constituent of the PV panel which is deposited by the process of plasma enhanced chemical vapor deposition (PECVD). The fabrication of a-Si layers occurs at maximum 200°C within a high vacuum chamber by flowing mixtures of the gases silane; heavily diluted process gases and hydrogen between high voltage electrodes, which initiates and sustains the plasma. Uniform p-i-n junction(s) is formed on top of front contact; TCO layer, in this a-Si PEVCD chamber.

The process gases are dissociated and largely consumed inside the chamber. The exhaust from the deposition process is first treated by burning the residual gas mixture ay 600-700 degree C. in a closed and controlled environment and then scrubbing the residue from the burning before releasing to the atmosphere.

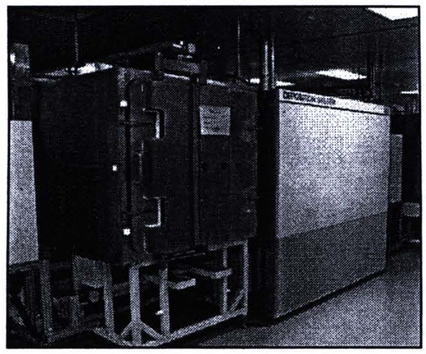


Figure 21 PECVD System

Figure 22 Cool-down Ovens

2.3 Cooling of the substrates: the cooling down of the substrates to workable temperature after deposition is done in the subsequent a-Si cool-down oven.

2.4 Patterning of P2 layers: the selective removal of conducting and semi-conducting thin-films on the glass substrate by scanning a focused green laser (Wavelength 532 nm) beams. After this process, the substrates will be deposited with back layers.

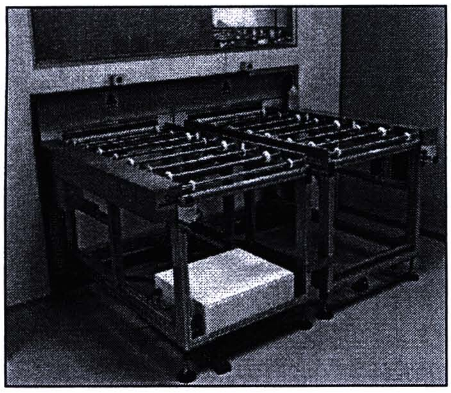


Figure 23 1st Green Laser Equipment

Figure 24 Sputtering System

2.5 Fabrication of back layers: the thin films which provide a diffusion barrier layer and electrical back contact on top of the thin-film a-Si:H is fabricated by magnetron sputtering within high vacuum chambers. Plasma is generated by flowing inert argon gas between high voltage electrodes. The resulting discharge sputters material from blocks of sintered ceramic transparent conductive oxides (ZnO) and metal (Al) layers on top of a-Si:H layers on the glass substrate.

2.6 Patterning of P3 layer: the selective removal of reflective and conductive as well as all semi-conducting layers on the glass substrate by scanning a focused green laser beams. After this process, the substrates which are now called "plates" will be sampling tested in special design I-V characterization equipment for PV cells.

Figure 25 2^{nd} Green Laser Equipment

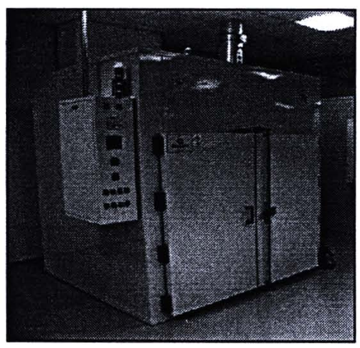


Figure 26 Anneal Oven

2.7 Annealing: the plates are heat treated in the oven at around 170°C for approx. 1-1.5 hours. This step will slightly improve the performance of the plates.

2.8 I-V characterization for PV cells: after the plates are heat treated, all plate is 100% tested in the I-V characterization equipment for cells to verify the previous process steps.

Figure 27 I-V Tester for PV Cells

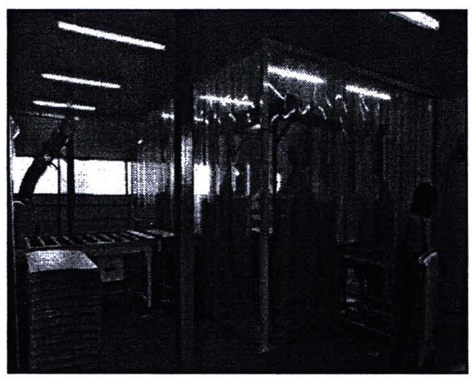


Figure 28 Edge Insulation System

2.9 Edge insulation: the removal of deposited materials along the edges of the plates to build-up high electrical insulation resistance of the PV modules by either sand-blasting or laser ablation method.

2.10 Ultrasonic bonding: the attachment of metallic foils along the opposing sides of the deposited glass plates for plus/minus electrical connections.

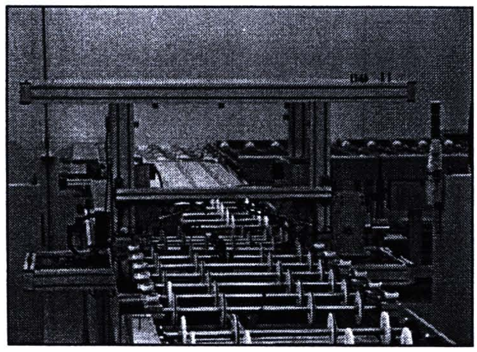


Figure 29 Ultrasonic Contact Bonder

Figure 30 EVA Lay-up

2.11 EVA Lay-up: laying-up of ethylene vinyl acetate (EVA) sheet between a deposited plate and a cleaned cover glass.

2.12 Encapsulation: the heating of the laid-up glasses in the laminator at 140-150˚C in order to encapsulate the active material and hermetically seal the PV cells from external environment.

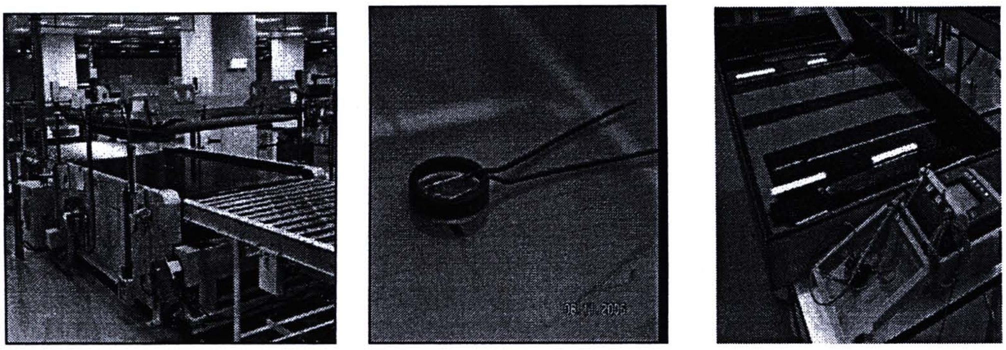


Figure 31 Encapsulation System, Wired Terminals and Wet Leakage Current Test

2.13 Wirings and potting: provide electrical connections to the foils for external circuit and potted-seal with electrical-grade silicone sealant.

2.14 Wet leakage current test: immersed testing of the PV modules to verify leakage current acc. to IEC 61646.

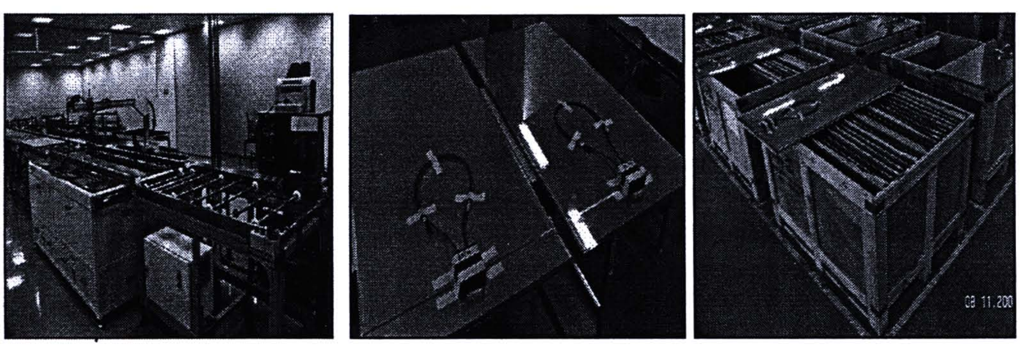


Figure 32 Final I-V Tester, Finished PV Modules and Packing

2.15 Final I-V test and packing: measuring of current and voltage characteristic prior to classification, labeling, sorting and packing.

The whole process takes approximately 40-50 hours from the beginning at the glass preparation to a finished PV module.

Raw and Consumable Materials

Key raw materials required for manufacturing of a-Si thin-film PV modules are:

Figure 33 Various Key Raw Materials

1. TCO glass

TCO (Transparent Conductive Oxide) Glass is an important raw material for a-Si thin-film PV module with one side coated with very thin layer of Tin Oxide (SnO_2). It serves as the front sheet of the module with high transparency for good sun light transmission. The layer is also served as a front contact with proper shunt resistance. The thickness of TCO glass can be from 3-6 mm. depending on the PV modules' design.

2. Cover glass

The cover glass is the normal soda-lime glass sheet used on the back side of the PV modules where the electrical connections are made sometimes through sealed junction box. Some manufacturers may use thin Tedlar or PVF sheet instead of the glass sheet.

3. Process gasses i.e. Silane, Phosphene, TMB, Hydrogen, Nitrogen etc.

These ultra high purity gases are required during the process for building-up of one or two p-i-n junction(s).

4. Metallic targets i.e. ZnO and Al

These metal targets are required during the fabrication of diffusion and back contact in the sputtering process.

5. EVA (Ethylene Vinyl Acetate) Sheet

With the aid of EVA through the encapsulation process, TCO and cover glasses will hermetically sealed the modules and protect the PV cells from external environment.

6. Metallic foil, silicone compounds, junction box, cables etc.

These materials are for completion of the electrical circuit to bring out electrical power out of the PV module.

From manufacturing experience of the above thin-film silicon PV modules in Thailand, the cost structure of the modules in percentage term can be summarized as follows:

1. Front glass superstrate or TCO glass	54%
2. Rear cover glass	8%
3. EVA sheet	12%
4. Metal targets	6%
5. Process gases	7%
6. Junction box and cables	6%
7. Miscellaneous parts	7%
Total	**100%**

From the above, we can see that TCO glass takes the major portion of the cost of the PV module. Study on cost and supply risks reduction on TCO glass should be performed and could be useful for this industry in the future. TCO glass will be described in more details in the latter part of this study.

Transparent Conductive Oxide (TCO) Glass

What is TCO Glass?

The word "TCO" is abbreviated from "**T**ransparent **C**onductive **O**xide". The TCO glass discussed in this study will be mainly focused on the TCO glass using as the superstrate of glass-to-glass thin-film a-Si PV modules.

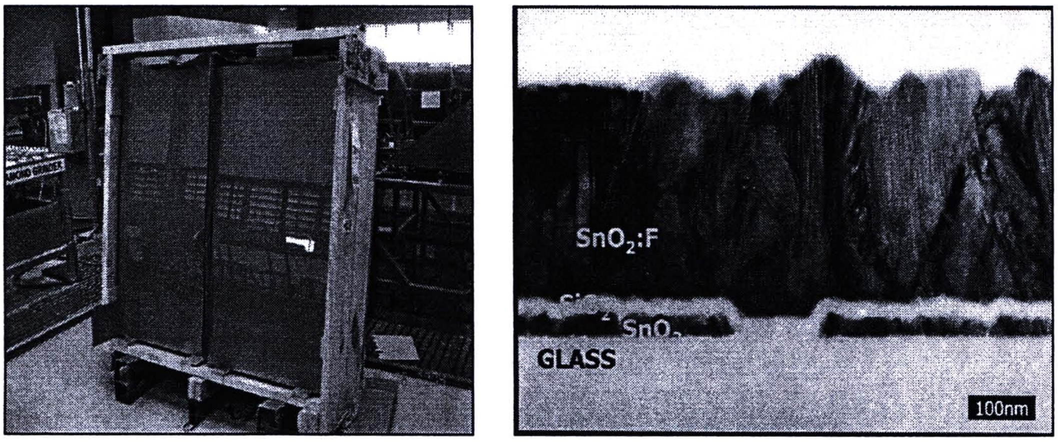


Figure 34 On-line Produced TCO Glass and its Microscopic Structure

TCO glass behaves as the front part of the a-Si thin-film PV module where sunlight hit its surface. The TCO glass shall have following roles and properties:

1. Serve as the window for visible light and front contacts of the PV cells
2. Has good electrical conductivity
3. Has high optical transmissions
   3.1 Absorption (A_{550})
   3.2 Haze (H_{550})
4. Has good adhesion property

Structure of TCO glass

Commercial TCO glass used as the superstrate for glass-glass a-Si PV modules made from a thin soda lime glass sheet with thin layer of SiO_2 and SnO_2 integrated on one side. The thickness of glass can be from 3-6 mm. depending on the design of the PV module. Thickness of SiO_2 and SnO_2 layers deposited on the glass surface by the APCVD method are approximately 100 nanometers and 500 nanometers respectively.

Property of Commercial TCO glass

Important properties of commercial TCO glass are as follows:

1. Sheet resistance: 10-15 ohm/square
2. Optical Transmission: more than 80% (400 to 700 nm)
3. Thickness variation : less than 10%
4. Haze: more than 10%

Typical Optical Transmission Spectra and Sheet Resistance of TCO Glass

The optical transmission of commercial TCO glasses for using for a-Si PV modules offered by AFG and Pilkington, USA, is higher than 80% over 400-700 nm regions. A-Si PV module has 400-700 nm band gaps, measurement of transmission of In-house TCO glass is therefore focused at mean value of 550 nm or so called T_{550}.

Typical sheet resistance of commercial TCO glasses from Pilkington is 15 Ohm/square (NSG-TEC15) while AFG offers 12-14 Ohm/square (ANS14) [5, 6].

The curves on left hand-side of Figure 35 show that the thin film with lower sheet resistance means thicker metallic layer but renders poorer light transmission.

In-house TCO glass in this study shall have sheet resistance within 12015 Ohm/square and optical transmission higher than 80% at 550 nm.

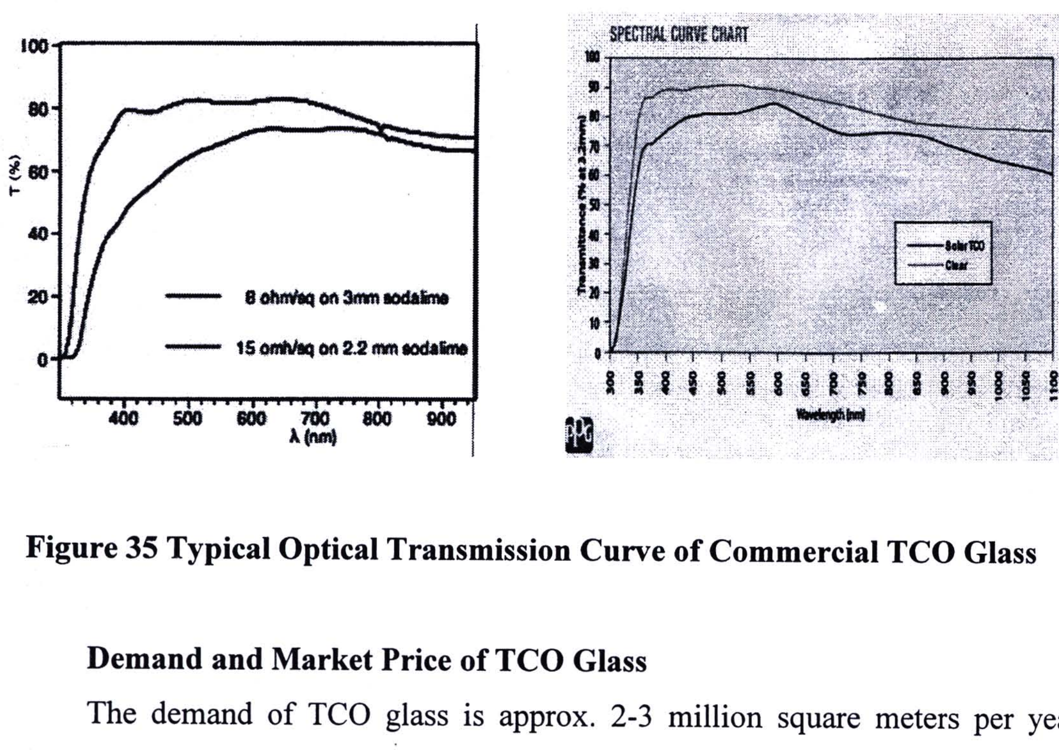


Figure 35 Typical Optical Transmission Curve of Commercial TCO Glass

Demand and Market Price of TCO Glass

The demand of TCO glass is approx. 2-3 million square meters per year. Unfortunately due to scarcity of solar-grade silicon, thin-film silicon PV panels which consume 100 times less silicon material becoming more and more popular and consequently push the strong increase of TCO glass consumption by 30 percent every year.

The market price for 3.2 mm normal soda-lime float-glass sheet in Thailand market is approx. THB 100-120 per square meter. The cost of producing the same glass shall be approximately within the same level from most float-glass plants worldwide. It is anticipated that after coating with tin oxide layer, the cost of the TCO glass should not be around THB 200 per square meter. However due to the fact that only a few large float-glass plants in the world are equipped with the APCVD facility to perform such coating and under such high market demand, the sales price has been controlled and set as high as THB 600 per square meter.

Since TCO glass account up to 54 percent of the PV module's cost, it is therefore very interesting to explore the opportunity to reduce the production cost of a-Si thin-film PV modules with in-house TCO glass coating. It is anticipated that the cost of in-house produced TCO glass would be lower than THB 400 per square meter. This means that minimum THB 200 can be save for each very square meter of TCO glass produced in-house.

Commercial On-line TCO Glass Production

1. Production of Float Glass [7, 8]

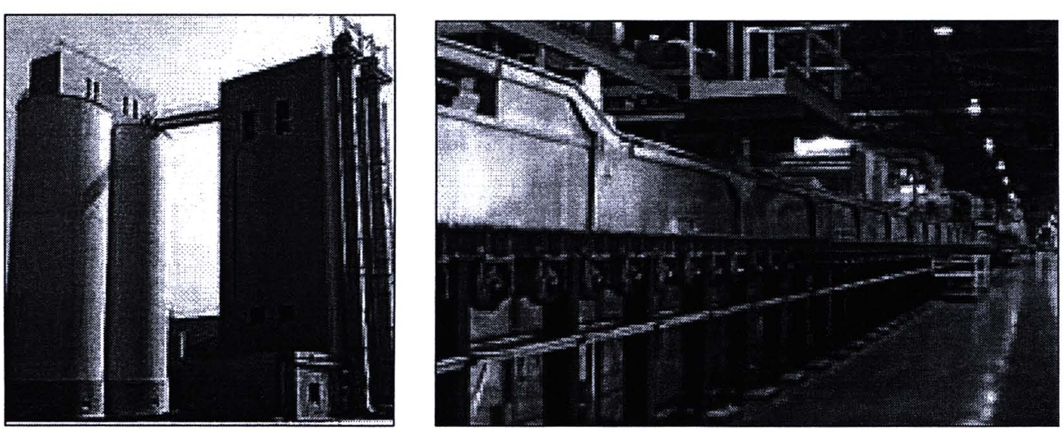


Figure 36 Float-glass Plant and Production Line

Today most TCO glasses are manufactured in the large float glass factories. Float glass manufacturing process was developed by Pilkington in 1959. The glass therefore gains its lustrous finish and perfect flatness by floating on a bath of molten tin in a chemically controlled atmosphere. The ribbon of glass is then cooled, while still moving, until the surfaces are hard enough for it to be taken out of the bath without the roller markings on the surface. The glass is then automatically cut and stacked, ready to be packed for distribution to local and international customers.

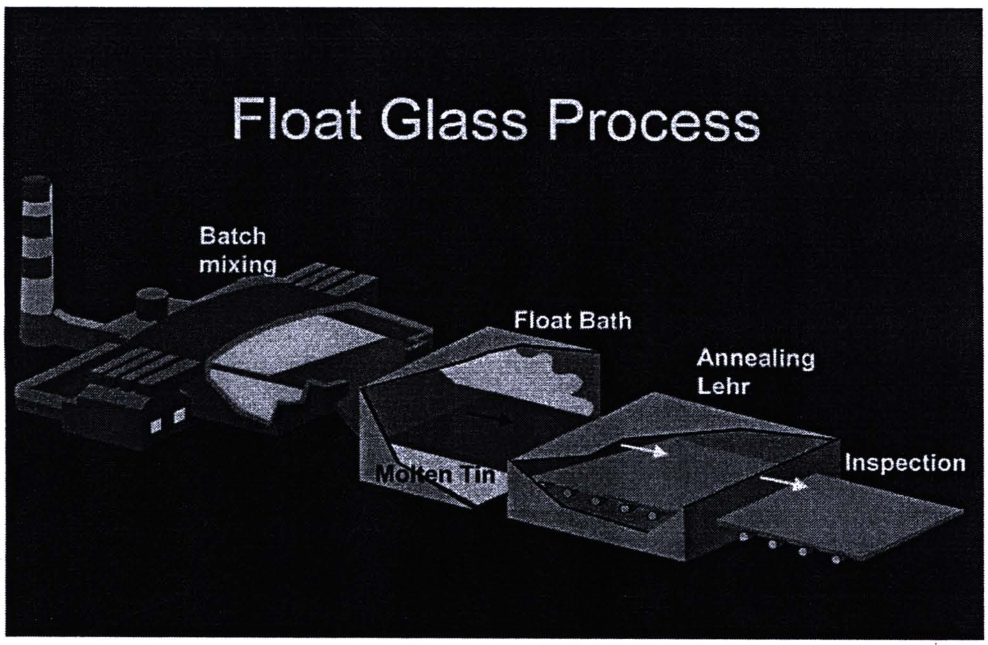


Figure 37 Conventional Float Glass Line

Followings are the process steps of float glass manufacturing.

1. Raw material feed

Sand (72.6%), soda ash (13.0%), dolomite (4.0%), limestone (8.4%) and a proportionate amount of cutlet (2.0%) are combined to form a batch.

2. Furnace

Batch materials are fed into the furnace. Full melting is achieved at around 1,600 degree C.

3. Float bath

A continuous ribbon of molten glass floats along the surface of molten tin.

4. Annealing lehr

The glass is annealed and gradually cooled to 200 degree C, to relieve stresses and prevent splitting and breaking in the cutting phase.

5. Inspection and Cutting

The glass ribbon is inspected and cut automatically as it moves along the rollers. Stacking and off-loading series of automatic stackers off-load the glass. The glass is then warehoused for distribution.

6. Distribution

The glass is distributed by road or rail and then sea for overseas destinations.

2. On-line Deposition of Tin Oxide Layer on Glass Sheet

TCO glass is accounted only approx. 1-5% of total annual float glass output. The factory normally produced TCO glass in a large single batch sufficient for at least a quarter or half-year demands. Produced TCO glass is then kept in the warehouse and will be distributed to the customers on bi-weekly or monthly basis according to the orders from various a-Si thin-film PV module manufacturers all over the world.

In the float glass production process, when the glass ribbon temperature in the annealing lehr reduced to approx. 650 degree C., Fluoride doped Tin Oxide (SnO_2:F) will be deposited directly onto the glass surface. This method of coating at high temperature is called "Pyrolytic Coating" which sometimes referred to as "Hard Coat".

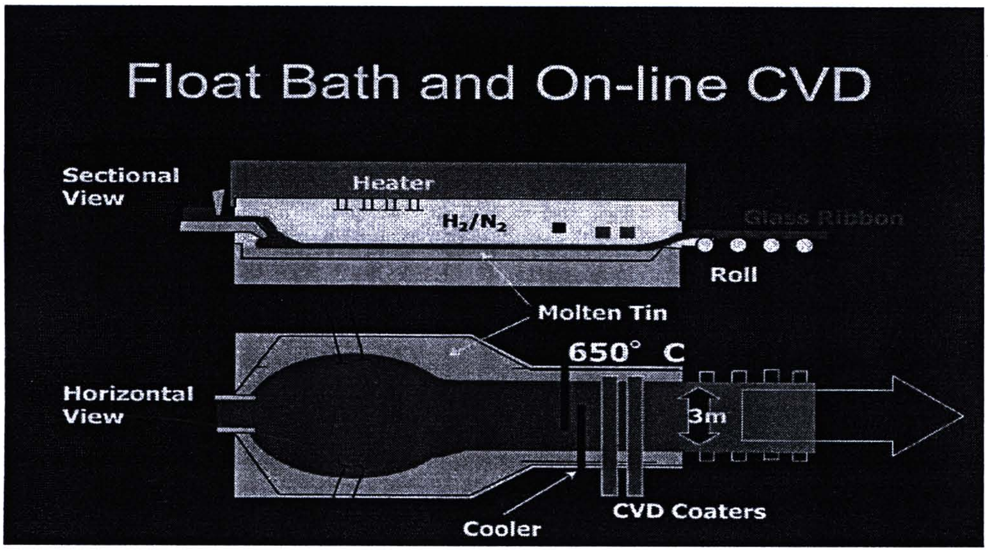


Figure 38 SnO_2 layer is being coated at 650 degree C.

From on-line coating process, TCO glass with thin layers integrated only on one side of the glass as shown in the Figure 38 will be produced. These layers are Tin Oxide (SnO_2) approx. 500-600 nm thick and an undercoat layer; SiO_2 which lies between the glass surface and the Tin Oxide layer. This SiO_2 layer will help preventing SnO_2 layer from peeling of the glass surface.

3. Thin-film coatings on Glass for other applications

For some applications when where an electrically conductive surface that at the same time offers a high optical transparency is required, this can be achieved by sputter-coating a thin conductive layer on indium-tin-oxide onto high quality glass substrates or so called ITO glass [9]. Followings are typical applications of ITO glasses:

1. Display technology such as OLED, PLED, LCD etc.
2. Transparent ITO electrode
3. ITO coated microscope slide
4. Circuit substrate
5. Micro structuring application
6. Transparent EMF/EMI/EMC/RFI/HF shielding glass
7. Flat antenna for mobile communication
8. Conducting glass

9. De-icing glass

10. Heatable ITO slide and cover slip

Due to different kinds of applications, ITO glass shall therefore posses following special properties:

1. Electrically conductive and optically transparent
2. High VIS-NIR light transmission
3. High quality glass substrate
4. SiO_2 barrier layer
5. Low roughness
6. High sheet resistance homogeneity
7. Uniform transmission homogeneity
8. Reflecting in the infrared range

The typical size of ITO glasses can be from 10x10 mm to 300x400 mm and sheet resistance from 5-100 Ohm/square [10]. These standard ITO glass are not suitable for a-Si PV modules and have not yet been used in the commercial production of a-Si PV modules.

In 2005, there was a study made on highly transparent and conductive SnO_2:F and In_2O_3 films deposited on glass by a group of researchers. The study was submitted and published in Brazilian Journal of Physics in 2006 [11]. Highly transparent and conductive thin film of SnO_2:F and In_2O_3 (ITO) have been prepared on glass substrates using the simple pyrolitic (spray) method. Through an exhaustive parameter study and using as diagnosis method for the film quality as the function of both, the transmittance and electric resistivity, the conditions to prepare the SnO_2:F and ITO films, with adequate properties to be used as transparent front contact for solar cells, were achieved. A relevant contribution of this work is related with the deposition of SnO_2:F and ITO films with the mentioned characteristics, using a solution synthesized in the laboratory by dissolving the precursor metals in HCl. Transparent Conducting oxide (TCO) thin film were comparable with those obtained , with transmittance greater than 80% and resistivity smaller than $7x10^{-4}$ Ohm.cm. In Figure 23 below compared the transmission spectra of SnO_2:F and ITO films, which the spectral transmittance of both types of TCO films (SnO_2:F and ITO) is greater than 80% in the visible and near infrared regions, indicating that from the optical point of view, both ITO and SnO_2:F films present properties for using them as optical windows and transparent electrical contact of thin film solar cells.

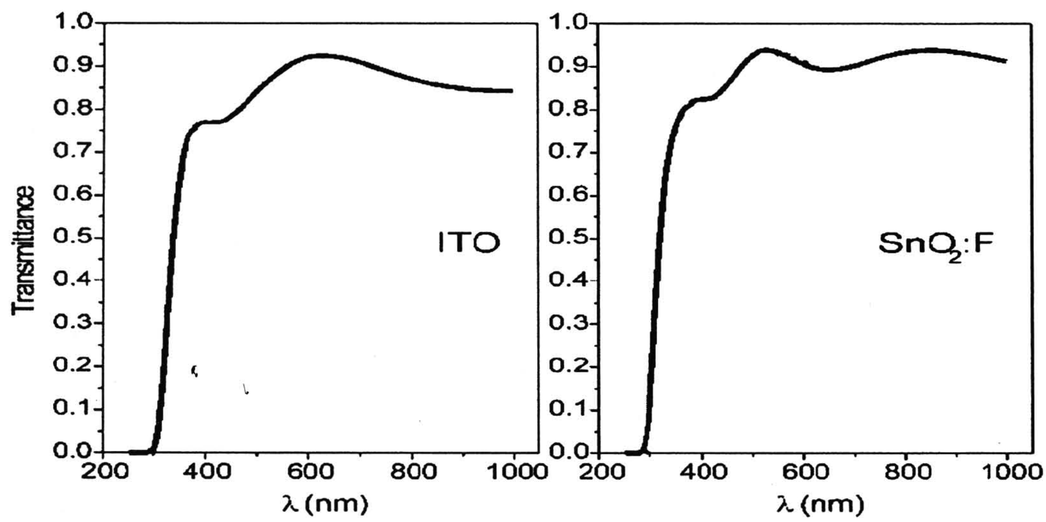


Figure 39 Comparison of Typical Transmission Spectra of ITO and SnO_2:F Films

In-house TCO Glass Production [12]

Coating of metallic layer(s) on the surface of soda-lime glass can also be done off-line outside the float glass factory. There are several methods for depositing tin oxide layer on glass substrate to produce TCO glass, but only two of these methods will be discussed in this study. These methods are

1. Atmospheric Pressure Chemical Vapor Deposition (APCVD) Method
2. Physical Vapour Deposition (PVD) or Sputtering Method

Both methods will be briefly described but in this study we will deeply discuss on in-house coating of ITO layer on glass substrate using PVD method in order to find new, simpler and lower cost to produce own TCO glass for a-Si PV modules manufacturing.

1. Atmospheric Pressure Chemical Vapor Deposition (APCVD) is the CVD process at the atmospheric pressure used to produce high-purity, high-performance solid materials. The process is often used in the semi-conductive industry to produce thin films. In a typical CVD process, the substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit. Frequently volatile precursors are also produced, which are removed by gas flow through the reaction chamber.

APCVD system is designed to uniformly deposit Silicon Dioxide (SiO_2) and Fluorine-doped Tin Oxide (SnO_2:F) films flat glass substrates. The designed deposition capacity shall be 100 nm of SiO_2, and 500 nm of SnO_2.

The system utilizes an electrically powered, multi-zone heating system to preheat the substrates up to a maximum temperature of 500°C prior to film deposition. Air and water-cooled muffle sections shall be used to cool-down the belt and substrates after deposition.

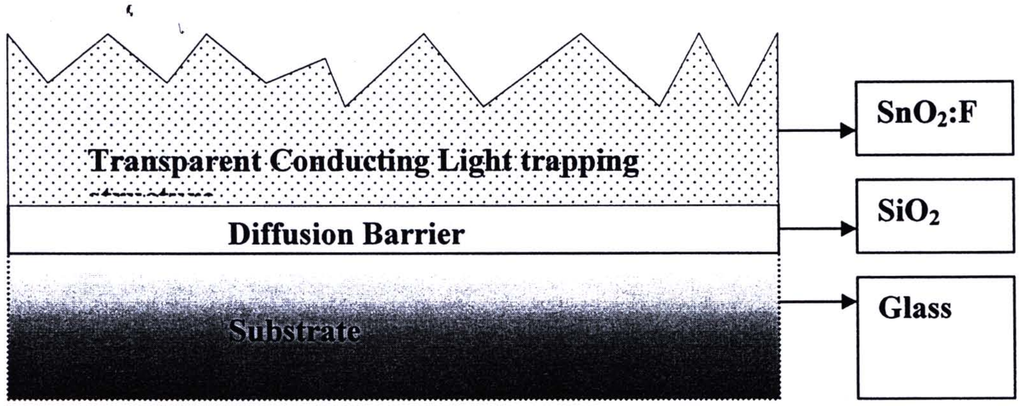


Figure 40 Schematic of TCO and Diffusion Barrier Bi-layer Structure

A muffle structure is used to produce a controlled atmosphere system to isolate and contain the APCVD process chemical flows. The muffle has four integral coating chamber structures, which will allow the installation and removal of individual chemical injector assemblies.

1.1 Consumable Materials:

1.1.1 Liquid chemicals : $SnCl_4$, H_2O, CH_3OH

1.1.2 Gases : SiH_4,O_2, N_2, HF, CDA

1.2 Basic Chemical Reactions:

SiO_2 layer	:	$SiH_4 + 2O_2$ →	$SiO_2 + 2H_2O$
SnO_2 layer	:	$SnCl_4 + 2H_2O$ →	$SnO_2 + 4HCl$

The chemical precursors for the SiO_2 film are Silane (SiH_4) and Oxygen (O_2). The primary chemical precursors for the SnO_2:F film are Stannic Chloride ($SnCl_4$) and de-ionized water. Fluorine is utilized as the dopant source. Methanol (CH_3OH) is used to control the rate of the $SnCl_4$-H_2O reaction. Mass flow controllers (MFC) control all process gas flows. Liquid chemical sources are delivered via heated bubbler modules with an N_2 carrier gas.

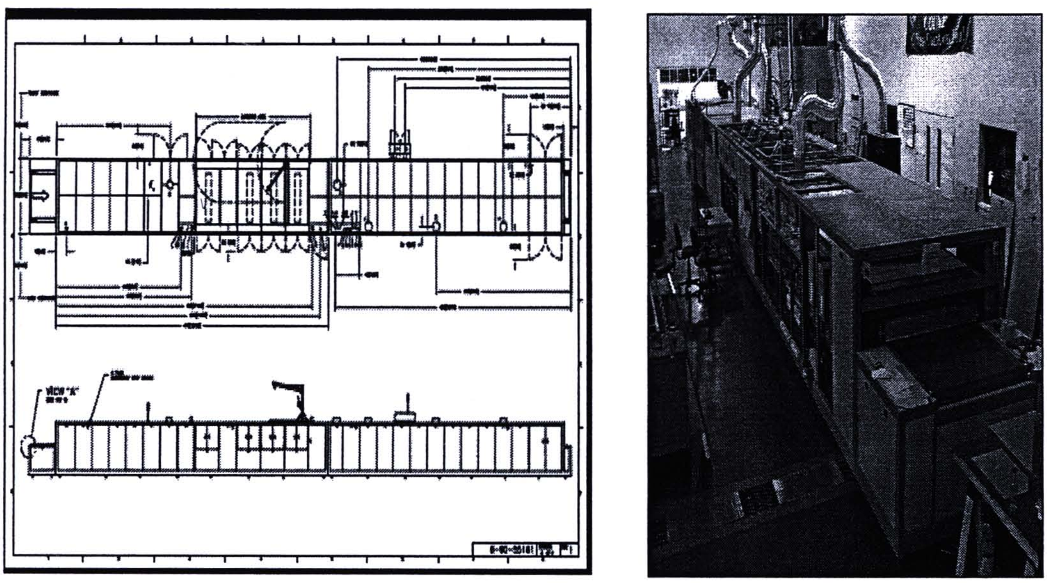


Figure 41 System Lay-out and Photo of Actual APCVD Equipment

The above APCVD TCO glass coating system is similar to the CVD system using for coating of SnO_2 layer in the in-line float glass plant when the temperature dropped down to 600-650 degree C. For in-house operation, glass sheet must be heated-up to 500-600 degree C to build-up similar conditions prior to the fabrication of the desired layers.

From cost estimation, TCO glass produced in-house by this method will have the cost 30-35% lower than the selling price of commercial in-line TCO glass. Due rather complicated chemical process and difficulty in controlling of layers' thickness uniformity as well as treatment of chemical waste, we will in this study concentrate the study to the PVD or sputtering method which is much simpler and easy to operate.

2. Physical Vapour Deposition (PVD) or Sputtering Method is a process whereby atoms are ejected from a solid target material due to bombardment of the target by energetic ions. This method is commonly used for thin-film deposition, etching analytical techniques. The coating method involves purely physical processes such as high temperature vacuum evaporation or plasma sputter bombardment rather than involving a chemical reaction at the surface to be coated as in the above chemical vapour deposition.

2.1 Consumable Materials:

2.1.1 Metallic targets : SiO_2, ITO

2.1.2 Gases : O_2, Ar, N_2, CDA

2.2 Materials and Process

Materials: Indium Tin Oxide (ITO) with a diffusion barrier between glass and TCO. The diffusion barrier is Silicon Dioxide, SiO_2.

Deposition of Tin Oxide layer on glass substrate can also be done with PVD or Sputtering method. A conveyorized reactive sputtering system is designed to uniformly deposit Silicon Dioxide (SiO_2) and Indium Tin Oxide (ITO) films onto flat glass substrates. The design deposition capacity shall be 25 nm of SiO_2, and 170 nm of ITO.

The system utilizes an electrically powered, multi-zone heating system to preheat the substrates up to a maximum temperature of 500°C prior to film deposition. After the glass substrate is heated to proper temperature, SiO_2 layer will first be deposited to form the diffusion barrier between glass surface and ITO layer which will later be deposited on top of SiO_2 layer. The depositions take place in the vacuum chamber with the controlled pressure of $5x10^{-2}$ to $5x10^{-5}$ mBar.

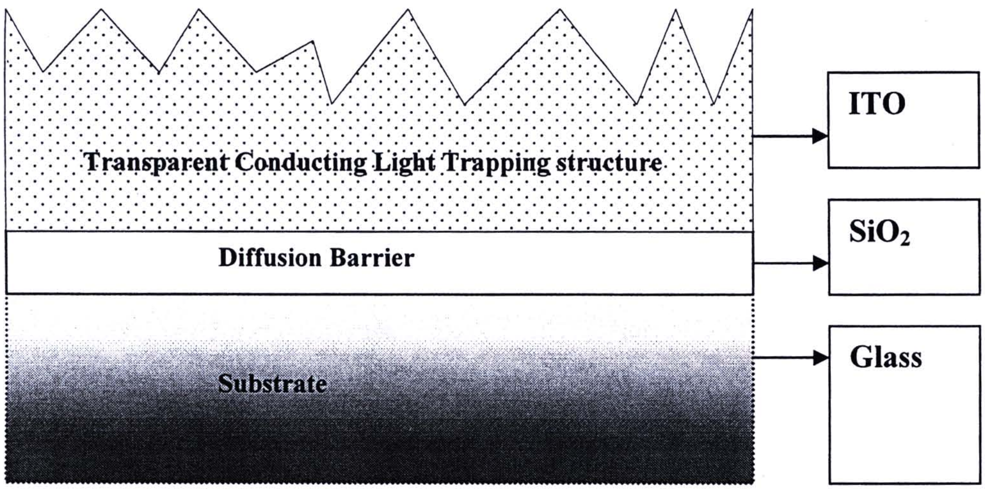


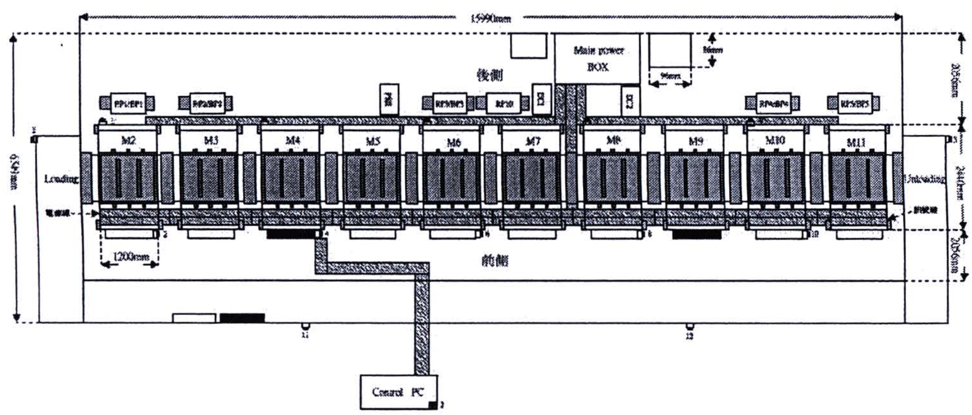
Figure 42 Schematic of ITO and Diffusion Barrier Bi-layer Structure

From the above sputter deposition process, the In-house TCO glass will have following properties:

1. Sheet resistance: ~10-15 ohm/square
2. Transmission: > 80%
3. Thickness variation: < 10%
   3.1 SiO_2 : ~25 nm
   3.2 ITO : ~170 nm
4. Haze: > 10%

The above properties satisfy the optical requirements for using to substitute and/or replace the widely used commercial in-line TCO glass in existing a-Si thin-film PV modules manufacturing plants.

2.3 Process/Equipment Lay-out



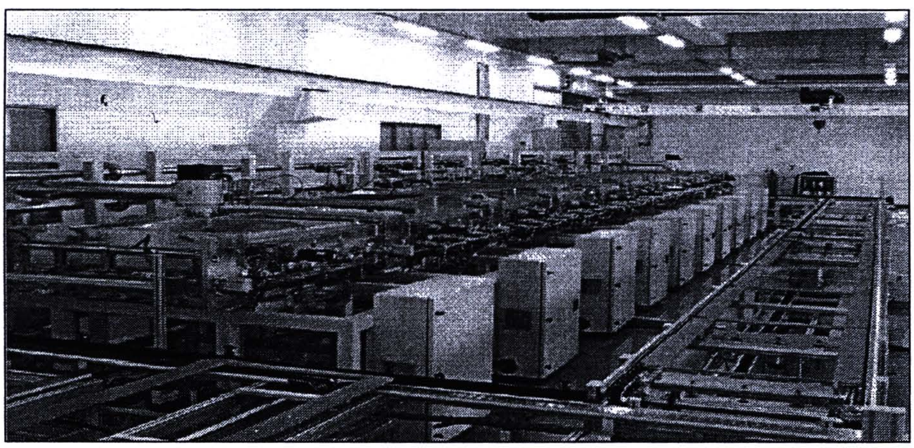


Figure 43 Typical Sputter System Process/Equipment Lay-out and Sputtering System/Equipment for Bangkok Solar