CHAPTER 3

THEORY OF PHOTOVOLTAIC MANUFACTURE

3.1 The production of Single Crystalline Silicon Photovoltaic Cell

From wafer to solar cells (Orchard et al. 2000 : Internet)

Most solar cells installed in Thailand are based on crystalline silicon. Silicon is one of the most abundant elements on the planet (in the form of quartz sand) and is an environmentally friendly material.

1. The starting material for making a solar cell is a thin slice of silicon called a wafer. Since the wafer is cut from a long ingot of silicon using a saw, its surface is damaged and dirty. The wafer must be smoothed and cleaned thoroughly before being used to make a solar cell. This process is called **etching**.

In this process, most environmental effects come from toxic chemicals and hazardous wastes which are involved in the process such as hydrofluoric acid (HF) which is used for wafer cleaning, dopant oxide removal, and diffusion tube and quartzarc cleaning. It accounts for a very large percentage of the total hazardous wastes.

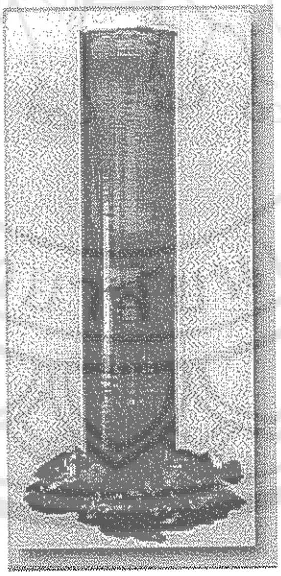

Figure 1. Silicon ingot

2. The first act for turning the wafer into a solar cell is to make one side into the equivalent of the positive "+" on a battery. This is done by applying a liquid containing the element phosphorous onto one surface in a process called **doping**. The wafer is heated in an oven to allow the phosphorous to worm its way into the surface of the silicon, in a process called **diffusion**.

3. The second stage of turning the wafer into a solar cell is to **print** electrical contacts on the front surface of the wafer. The contacts are made of a metal that collects and conducts electrons which are generated when sunlight strikes the cell. Since we do not want to cover the whole front surface with metal since that would stop any light from getting into the cell, a grid of very thin lines is printed over the wafer leaving as much of the silicon surface exposed as possible.

4. The final step on the front surface is to coat the wafer with a special material that stops as light as possible from being reflected away from the cell, called an **Anti-reflection coating.**

5. The cell is turned over and the negative "-" side of the solar battery is formed. This is done by coating the surface with aluminium in a process called **metallisation**. This is heated in an oven to make sure the aluminium is absorbed into the surface of the silicon. This surface can also have the purpose of transporting electrons back into the cell. The wafer is then `baked' in an oven in a process called **firing**.

6. In the final step, the positive and negative sides of the solar `battery' are **Isolated** from one another. Each completed solar cell is then **tested** under simulated sunlight to make sure it works. Working cells then go on to be assembled into a solar module.

From Solar cells to modules

Completed and tested solar cells are assembled together to make modules. Modules come in different sizes depending on the application there are to be used for. Common sizes include anything from 36 cells to 72 cells.

The cells must first be **electrically connected** together. This is just like connecting batteries together to get a greater power output - the negative side of one cell must be connected to the positive side of the next cell, and so on, until all the cells are connected.

The connected "mat" of cells is then **laminated** into a protective housing. The housing consists of a specially hardened, highly-transparent glass in front of the cells and layers of foil behind the cells. The mat of cells is itself embedded in a special plastic material called Ethylene-Vinyl Acetate (EVA) which protects the cells against damage from humidity and UV light. These layers also ensure the electrical safety of the module. The whole "sandwich" is then pressed together under vacuum at raised temperatures in a laminating machine.

The so-called "laminate" is then **framed**, often with aluminium, to give it rigidity and strength. This allows the module to be easily assembled into another structure, such as the roof of a house. In the whole process of course, we must not forget the electrical connections from inside the module to the outside world. A small unit mounted on the back of the module allows us to make connections directly from the cells in the module to another neighboring module or directly to the system we want to power with solar electricity. The whole module is then tested and checked before it leaves the factory.

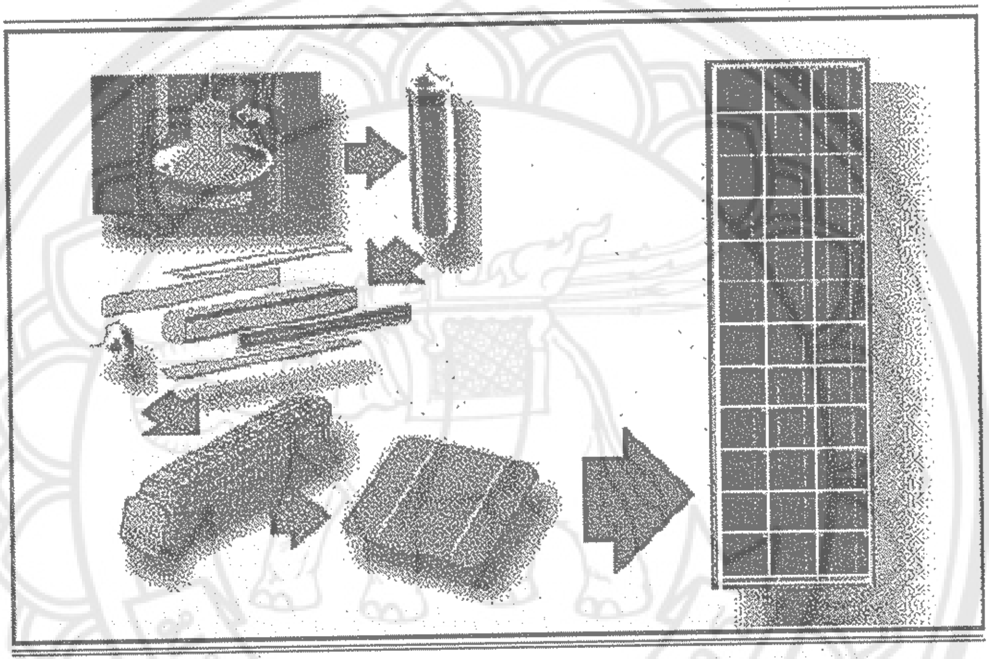

Figure 2. The process from Silicon ingot to a PV module (Orchard. 2000 : Internet)

3.2 Environmental impact from Silicon Photovoltaic Manufacture

Although PV power systems do not require finite energy sources during their operation, a considerable amount of energy is needed for their production. The environmental issues associated with this energy use for PV manufacturing will also affect the environmental profile of PV power system. After the energy used in processes, the CO_2 will emit from the process of combustion and it is a major greenhouse gas. There are other environmental effects from PV manufacture besides the greenhouse effect which is from power required in the PV production process.

With the worldwide Photovoltaic (PV) solar energy market expanding rapidly and the increasing demand outpacing supply, the crystalline-silicon solar PV module finally becomes a commercially viable product. Most of the newcomers and the capacity expansions of existing producers are still based on either single-crystal silicon grown by the Czochralski (Cz) method or polycrystalline silicon by casting though the very different thin film process is increasingly being used. Because solar electricity generation is a large area application, it is likely the PV industry will eventually use more silicon than even the integrated circuits (IC) industry. It is important at this stage to review the environmental impact of the rapidly growing silicon based PV industry to find the opportunities for improving energy efficiency and reducing its environmental impact.

There are four types of crystalline-silicon solar cells: single-crystal, polycrystalline, ribbon and silicon film deposited on the low-cost substances. In 1997, the market share of worldwide PV cell and module shipment for the four types of crystalline-silicon solar cell were 49.6% for single-crystal, 34.0% for polycrystalline, 3.2% for ribbon, and 0.4% for silicon film. Crystal growth from a silicon melt generates small amounts of waste. The main concern is the energy required and the amount of argon gas used during crystal growth. Electricity and argon needed for Cz growth for single crystal cells is the highest among the four types of silicon materials. Recently, however the world's largest manufacture of Cz silicon solar cells, Siemens Solar Industries, announced a joint project with the Northwest Energy Efficiency Alliance to cut the amount of electricity used to grow crystals and yield savings of 40% to 50%.

Wafer Slicing and Cleaning

- Wafer Slicing

In the last six years or so, the PV industry has changed from using ID saws for wafer slicing to using multiple–wire saws. In this process, ingots are bonded to a ceramic submount by hot-melt adhesive and sliced into wafers using multiple steel wires to which an abrasive slurry is fed. Multiple-wire saws can improve wafer yield per unit length of ingots by over 50% because of lower kerf loss and thinner wafers. However, wafer slicing is still one of the most expensive processes in silicon solar cell manufacturing because of the large quantities of consumables (stainless-steel wire and abrasive slurry) and the kerf loss. The slurry is composed of silicon carbide (SiC) and mineral-oil-based or glycol-based slurry vehicle. Oil slurry is commonly used by the PV industry instead of the water-soluble, glycol-based slurries more commonly used by the IC industry. The oil-based slurries produce more environmentally damaging wastes and require more extensive wafer cleaning. The added cost and the process changes needed for the PV industry to switch over to glycol-based slurry need to be investigated. Methods of proper disposal or recycling of the stainless-steel cutting wire also need be studied, as does the effective recovery of the SiC in the slurry. The development of water-base slurries will also help reduce cost and environmental damage.

- Wafer Cleaning and Etching

The cost of chemical waste disposal is high. It is important for the PV industry to find ways to reduce chemical consumption and waste generation through source reduction, recovery, recycle, reuse and substitution. Because wafer cleanliness for PV is not as critical as for IC manufacturing, a safe choice, in terms of making sure the highest quality and most extensive cleaning procedures are used, is not necessarily the right choice in terms of cost reduction and environmental safety. Certain methods, such as dry cleaning processes, although not adequate for the IC industry standards, may be sufficient for the PV industry. For example, centrifugal shear carbon dioxide cleaning is worth considering as an alternative to organic solvent and/or hot detergent cleaning methods for wafer degreasing and cleaning after slicing. This process uses carbon dioxide in three coexisting phases: liquid, supercritical, and dense-gas. Operating temperature ranges from 298 K to 310 K, and pressure ranges from 56 atm to 100 atm. CO_2 gas is non-flammable, non-combustible and non-corrosive, and is abundant, inexpensive and reusable. Compressing CO_2 at about 70 atm and at temperatures below its critical temperature (305 K) liquefies the gas. Compressing CO_2 above its critical temperature and pressure (72.9 atm) does not cause a phase change, yet the density of the gas may be liquid-like. Static and dynamic cleaning processes employing the multi-phase CO_2 system have been developed. The excellent cleaning abilities derive from a combination of solvent cleaning power and, in the dynamic processes, by physical cleaning action. Although CO_2 at these pressure and temperature conditions presents densities comparable to other cleaning agents (about 500 g/L), it has a viscosity comparable to gases. For instance, it is 10 to 30 times smaller than 1,1,1-trichloroethane (TCA).

For texture etching and/or surface damage removal, most of the PV industry has been using sodium hydroxide etchant. NaOH etchant is considerably cheaper and easier to dispose of than the conventional hydrofluoric-nitric-acetic acid etchant. In an National Renewable Energy Laboratory funded program, Siemens Solar Industries found that the caustic waste per wafer generated by the saw-damage-removal etching process was reduced by about 20% after the switch from ID saws for wafer slicing to multiple-wire saws. This is because the wire-sawn wafer requires less etching to remove saw damage.

The Photovoltaic Device Fabrication Laboratory (PDFL) at Sandia Laboratories has had a program to continuously monitor and reduce chemical usage since the laboratory began operations in 1989. The chemical waste generation has been reduced by nearly 75% since 1990 by using three procedures: (1) eliminate and/or replace hazardous chemicals, (2) recycle chemicals and (3) reduce usage of remaining hazardous chemicals. A key feature of this effort was the use of statistical experimental designs to screen chemicals for their effectiveness in wafer cleaning and statistical process control to ensure that chemical-reduction changes did not impact the manufacturing processes. An experiment was performed to use statistical designs to examine the effect of 22 different parameters associated with chemical cleaning of wafers. The experiment was able to eliminate a popular, but expensive, chemical (hydrogen peroxide) that is widely used in the IC industry for cleaning silicon wafers. Subsequently experiments and changes in procedure have eliminated sulfuric and phosphoric acids from PDFL.

Hydrofluoric (HF) acid solution is used for wafer cleaning, dopant oxide removal, and diffusion tube and quartzarc cleaning. It accounts for a very large percentage of the total hazardous waste generated by silicon solar-cell manufacturing. It is possible to reprocess used HF solutions using reverse osmosis.

Solar Cell Processing

For junction diffusion, either a belt furnace or a tube furnace is typically used. Tube furnaces traditionally use a $POCl_3$ liquid source dopant, which generates toxic C_2O_5 and Cl_2 effluents and requires frequent cleaning of diffusion tubes using HF solutions. Belt furnaces are more environmentally benign because they can use wafer-soluble, non-toxic, spin-on or spray-on dopants or vapor dopants and do not require HF cleaning. Optically enhanced doping methods, such as solar furnace doping are also environmentally benign alternatives.

Edge trimming to removal electrical shorts between the front and the back junction can be done either by laser cutting or plasma etching. Because of its very high throughput, CF_4+O_2 plasma etching is commonly used by the PV industry. However, CF_4 is one of the perfluorinated compounds (PFCs) that has no known natural destruction mechanisms, and thus, has a large global warming potential. The PV industry needs to either find an alternative to the CF_4 and O_2 plasma etch or improve the effluent treatment to include PFC capture and recycling.

Vacuum evaporation, plasma deposition, atmospheric-pressure chemical vapor deposition, and spin-on liquids can deposit antireflection coatings. A safer alternative, chlorosilane, which is non-pyrophoric, has been used successfully by the IC industry for silicon nitride depositions.

For metal electrodes on the solar cell, it is not desirable to use silver-tin-lead solder baths after screen printing to enhance the conductivity of the metal grids because of the added lead content to the cells.

Module Assembly

- Non-Clean Flux

Flux, typically a derivative of pine resin, is applied to cell interconnection strips before soldering to act as a deoxidizer and to ensure better adhesion between the solder and solar cell. Conventional flux leaves residues on the cell surfaces that need to be cleaned with a chlorofluorocarbon (CFC) compound. CFCs are known to cause ozone depletion in the atmosphere. Recently, water-soluble fluxes and "no-clean" fluxes, low-residue fluxes, that can be left on the solar cell after soldering have become widely available. Siemens Solar was able to eliminate the CFC usage in the manufacturing facility by switching from conventional solder paste to a "no-clean" solder paste. The no-clean process both eliminates the environmentally damaging CFC emissions and reduces costs. Siemens Solar also found that by using a water-soluble flux, the CFC usage could be reduced by about 60% over a conventional flux.

However, it appeared that a water rinse of the cells caused retained moisture during the lamination sequence and caused module reliability problems.

- Lead-Free Solder

Lead is a well-known hazard to human health. When disposed of in landfills, it can leach into soils and pollute ground water. It is important for the PV industry to remove or minimize the use of lead in modules so that proper disposal at the end of module life will not become a problem. For example, some European countries have proposed a ban on the landfill disposal of electronic products containing lead. There are two sources of lead in a crystalline-silicon PV module: solder-dipped electrodes and solder-coated copper ribbons. The practice of dip-coating solar cell contact electrodes is no longer necessary with modern screen-printed electrodes, but it is still used by a significant number of module manufactures. The lead-tin solder that coats the surfaces of copper ribbons for tabbing strips is to prevent the oxidation of the copper and to improve the solderability of the ribbons. However, lead-free alternatives to lead-tin solder have been investigated extensively by the printed-circuit-board industry.

Table 3. Material composition of solar PV systems

Process	Capacity (Mwel)	Material composition (t/Mwel)					Source
		Glass	Silicon	Steel	Cement	Plastics	
PV-small	0.01	75	25	170	0	50	ÖKO (1994)
PV-large	1.00	55	25.5	110	545	50	ÖKO (1994)

Source: Environmental Manual For Power Development, GTZ and öKO (1994)