

# Solar Cell Standard and Improved Manufacturing Processes

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**Abstract** - As a result of high manufacturing cost, the application of the solar cell in terrestrial use has been slow to take-off. Solar cell production cost is high because the solar cell silicon and the semiconductor silicon undergo similar manufacturing processes even though the solar cell can tolerate impurities more than the semiconductor. The silicon for the semiconductor industry is required to be ultrapure. The widespread use of solar cells in space applications may be attributed to its high power-to-weight ratio. The standard method of manufacture of the silicon includes the reduction of sand to metallurgical grade silicon, purification to semiconductor grade silicon, conversion to single crystal silicon wafers, processing into cells and encapsulation into modules. The current reduction in the cost of silicon cell may be attributed partly to improvements in manufacturing processes and to economy of scale. It is thought that graphene because of its superior properties will eventually replace silicon.

**Index Terms**-photovoltaic, metallization, graphene, silane, module, semiconductor, silicon

## I. INTRODUCTION

Although the photovoltaic effect was discovered over hundred years ago, its application terrestrially has been slow to take-off because of the high cost in the manufacture of silicon cells. The manufacturing methods used are the same as those employed in the semi-conductor industry even though the silicon for the solar cell would tolerate more impurities than its semi-conductor counterpart. The high cost notwithstanding, in recent years, photovoltaic technology has steadily been gaining ground as an alternative and sustainable way to produce electricity. Photovoltaic production has been doubling every two years, increasing by an average of 48% per year since 2002, making it, as Ferrotec [1] has noted, the world's fastest-growing energy technology. The need for alternative, renewable and environmentally friendly energy source, has been necessitated by global warming and the call for individuals to reduce one's carbon footprint. The first use of solar modules to power satellites was in 1958 and today, solar power technology is still the primary source of energy in space stations. The widespread use of solar cells in space applications may be attributed to their higher power-to-weight ratio compared with any of the other competing technologies. However, this success was also responsible for the sluggish progress in global applications because space users were willing and ready to pay a premium for the best possible cells available. As a result therefore, the semi-conductor industry had no incentive to invest in low-cost solutions albeit with reduced efficiency that might potentially reduce instead of increase their profit margin. The situation whereby the semiconductor sector largely determined the price of cells

remained for quite some time. The stringent requirements of cell performance and reliability in the semiconductor and satellites communications sectors led to standards in the processing sequence of the cells which remained virtually unchanged until interest in integrated circuit and terrestrial use developed. Application in these later sectors has introduced some significant changes in the standard method of fabrication of the cells. The move to integrated circuits in the 1960s led to the availability of larger boules at lower relative prices and correspondingly a fall in the price of the resulting cells. However these had limited effect on prices because the estimated cost of the cell in 1971 was still as high as \$100/W, Perlin [2]. The majority of modules used today are based on crystalline silicon cells. The purpose of this study is to review the standard method of manufacture of silicon solar cells that is based on the semiconductor industry together with other innovative processes in the manufacture of silicon solar cells. These innovations and the economy of scale may be responsible for the dramatic fall in the price of solar cells in recent years.

## II. STANDARD MANUFACTURING METHODS

The standard method for the manufacture of silicon cell based on the semiconductor industry covers the following: sand reduction to metallurgical grade silicon, purification to semiconductor grade silicon, conversion to single crystal silicon wafers, processing into cells and encapsulation into modules. Fig. 1 summarizes the steps taken in the production process.

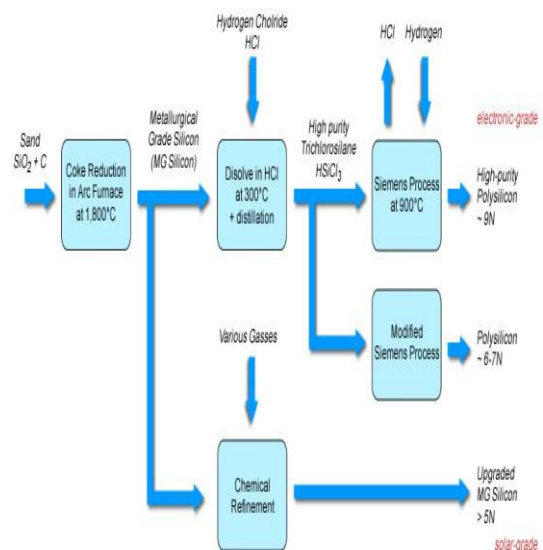


Fig. 1 Schematic Silicon Manufacturing Processes (source: Green Rhino Energy [ 3])

#### A. Metallurgical Grade Silicon

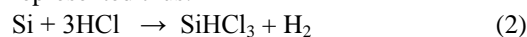
A major constituent of sand, silicon dioxide is the source of material for the extraction of silicon. In the commercial extraction process, the crystalline form of silicon dioxide called quartzite is used. The manufacturing is carried out in big arc furnaces in a reduction process. Lund et al [4] have summarized the chemical reactions that take place with the equation below. Equation 1 is a reduction reaction process in a furnace environment packed with a mixture of quartz and carbon.



After further purification the molten silicon is poured into shallow troughs for solidification. This is the metallurgical grade silicon which, according to Green Rhino Energy [3], is about 98% pure and it is mainly used in the steel and aluminum industries. The reduction process is claimed to be energy efficient.

#### B. Semiconductor Grade Silicon

The silicon required for semiconductor and solar cell is supposed to be purer therefore the metallurgical silicon grade is further refined to improve its purity. The standard method used for further purification is the Siemens process. The metallurgical silicon is refined and condensed by fractional distillation before extraction of the ultrapure silicon from the refined product. In this stage of the processing, a bed of fine metallurgical silicon in the presence of copper as a catalyst is fluidized with hydrochloric acid. The reaction can be represented thus:



The resulting gases are condensed and the liquid undergoes multiple fractional distillations to produce semiconductor grade trichlorosilane ( $\text{SiHCl}_3$ ). Semiconductor grade silicon is obtained by depositing the material in a fine grained polycrystalline form on a heated silicon rod when a mixture of the trichlorosilane and hydrogen is heated. The reaction is represented by the following equation:



This step requires considerable amount of energy and the yield as well, is low usually about a third. This can account for the massive increase in price compared with the metallurgical grade.

### III. THE WAFERS

The Czochralski process is the method used to transform the silicon from the last stage to single crystal form. The silicon produced in the last stage is still in the polycrystalline form but what is needed by the semiconductor electronics industry should not only be pure but in the single crystal form and without defects. This is achieved by melting the polycrystalline silicon in a crucible with the trace element of the dopant required in the final silicon added.

#### A. Single Silicon

Boron, a p-type dopant is normally added in the case of solar cells. In this stage close temperature control is a requirement and from the melt a single crystal of silicon in cylindrical form can be pulled. The crystal silicon is cylindrical and could be up to one metre in length. For the solar cell to absorb from most of the appropriate wavelengths of the sun, there is a requirement for a minimum thickness and this minimum is of the order of 100  $\mu\text{m}$ . Using the standard manufacturing technology, it is difficult to cut the wafers to this small thickness for a reasonable yield. Therefore more than half the silicon is lost in converting to the single crystal wafers. The wafers may be polished after cutting to remove saw marks but it has been found that rougher cells absorb light more effectively; therefore some manufacturers have chosen not to polish the wafer any more. Rectangular or hexagonal wafers are sometimes used in solar cells because they can be fitted together perfectly, thereby utilizing all available space on the front surface of the solar cell.

#### B. Solar Cells

Any damages introduced during the wafering process are removed by etching and cleaning. In addition to the p-type impurities introduced in the earlier stage, the n-type impurity must be introduced to give the p-n junction. The impurity is phosphorus and this is introduced by bubbling a mixture of small oxygen and phosphorus oxychloride ( $\text{POCl}_3$ ) through a furnace tube in which the wafers are stacked. An oxide layer containing phosphorus grows on the surface of the wafers. At the temperature this process is carried out, between 800 and 900°C the phosphorus is enabled to diffuse into the silicon to displace the boron near the surface. The oxide layer is subsequently removed from the sides and back of the cell. Metal contacts are then attached on the n-type as well as the p-type region by vacuum evaporation technique. The contacts are usually made of three layers of metal with palladium sandwiched between titanium at the bottom and silver at the top. For good adherence and low contact resistance, the contacts are sintered. Finally a thin antireflection (AR) coating is deposited by the same vacuum evaporation process. The process is however too labour intensive and the vacuum evaporation equipment is also expensive in comparison with its throughput. More importantly, only a small fraction of the material that is evaporated end up where it is supposed to because of the difficulty of controlling the evaporation process and this could be expensive especially when dealing with costly raw material such as silver.

#### C. Solar Cell Modules

The solar cells are usually encapsulated for mechanical rigidity for the brittle cells and the flexible interconnections. The encapsulation also provides electrical isolation for the generated voltages. The ultimate operating life of the module depends on the durability of the encapsulation. The

encapsulation must in addition possess ultraviolet (UV) stability, tolerance to temperature swings and thermal shock without stressing cells to fracture, self cleaning ability, and resistance to abrasion as well as keeping cell temperature low. The module encapsulation may include a structural back, shock absorbent material, adhesive and transparent cover. The structural back may be made from wood or epoxy board. The top cover is usually made of a transparent material such as glass. Often multiple interconnections are used in order to provide redundancy. It is designed to provide stress-relief loops in the interconnections. Module performance is cell temperature dependent and the module design could affect the cell temperature. Performance is adversely affected by increasing temperature. Most commercial modules allow the cell temperature to rise 30°C above ambient under full sun irradiation when the module is mounted on open frame. If the module is roof mounted the operating temperature would be higher. Some of the factors that could hasten module degradation include: cell breakages caused by excessive mechanical stress, thermal fluctuation, rain storm, decolouration of encapsulation material, accumulation of dirt on modules with soft top surfaces and breakages due to inadequate relief between the interconnections. The life and performance of the module could be affected by the circuit design of the cells interconnections. Mismatch loss is due to mismatches in the operating characteristics of the cells that are interconnected. This is the most significant loss of the cells in series and the resulting effect is that the combined output power is less than the sum of the individual constituents. Overheating is a possibility within the poorest cells in series and this can damage the encapsulation due to localized temperature hotspots. Shadowing and cracking of the cells in the module could also create similar problems. These adverse effects could be reduced by the use of bypass diodes or series paralleling.

#### IV. IMPROVEMENTS IN MANUFACTURING

The flaw in the silicon cell manufacturing method described so far does not only involve many processes but also is energy intensive. Combined, these result in high manufacturing cost. The focus therefore has been directed to ways of not only reducing the costs but also simplifying the processes.

##### A. Cost and Process Reduction

Unlike in semiconductor transistors and integrated circuits where performance is a premium and material cost is relatively unimportant, it is possible to consider a trade-off between performance and cost in the case of the solar cell. Impurities in the solar cell generally introduce allowed levels in the forbidden gap and therefore act as recombination centres. Cell efficiency will be decreased when the number of such centres increases. However, Lutwack [5] has reported the effect of secondary impurities on the performance of silicon solar cells. From this work, it can be deduced that the

concentration of impurities normally found in solar cells is not high enough to significantly degrade efficiency therefore reduction in manufacturing cost of solar cells can be achieved without major drop in performance. Modification to the standard manufacturing process include those by Union Carbide, Lorenz[6], which is claimed to reduce cost and energy used to one-fifth and one-sixth respectively and involves the preparation of silane (SiH<sub>4</sub>) from metallurgical grade silicon followed by the deposition of silicon. Similar work by Batelle Columbus Laboratories was based on the reduction of silicon tetrachloride by zinc. The standard ingot is cylindrical and the method of slicing to wafers is inefficient that over half of the ingot is lost in the form of wastages. The wafers cannot as well be densely packed when encapsulated in the module unless trimmed into hexagons or rectangles. Part of the modification is the production of ingots with square section in a process similar to casting. Careful control of the rate at which the molten silicon solidifies is required as in the heat-exchanger method, Ouadjaout et al [7 ] to obtain solar cells of quality comparable to those made from the purest semi-conductor grade silicon. Several techniques have been developed for the formation of the silicon directly into sheets or ribbon using such methods as the edge-defined film-fed method. The dendritic web method is devoid of the problems associated with the edge-defined film-fed growth method which include poorer crystallographic quality compared with the standard process product and the molten silicon reacting with the graphite die to degrade the properties of the fabricated cells, Seidensticker [8]. Another development is the reduction of reflection losses by the use of silicon wafers with textured surfaces created by etching, Ibrahim and El-Amin [9]. For increased throughput, the p-n junction as well as other stages in the manufacture of the silicon cell could be achieved by continuous conveyor belt process instead of the standard batch method, Hanoka [10].

##### B. Further Cost and Process Reduction Measures

In addition to improved methods in the manufacture of silicon cells, there has also been substantial investment in pioneering new technologies and manufacturing practices in order to reduce the cost of PV, improve material efficiencies and enhance process simplification. Some of these are still in the laboratory stage while the others have matured to production. As part of the effort to reduce the high cost of solar sell AstroPower in a program administered by the NREL, has developed new techniques for solar cell manufacturing Culik et al [11]. The major technical aim of this program is the replacement of batch processing with continuous in-line belt processes. The program introduced new procedures and equipment covering many processes including in-line wet chemical processes, metallization, sheet fabrication, solar cell processing, and module assembly, testing and recycling of Silicon-Film sheet materials. Also installed and commissioned is screen printing equipment, large belt furnaces for belt-gettering, belt-diffusion including

front and back metallization process steps. The program claims to have reduced the costs for Silicon-Film modules produced by AstroPower through the design of a new, lower cost, junction box.

Writing in the Renewable Energy World, Montgomery [12], has reported of a company called “1366” that has devised a means of reducing the overall cost of multi-crystalline silicon solar wafers by a third by using shallow instead of the standard 0.65m long and 0.32m deep quartz crucible. The deep crucible leads to a lot of material wastage during the chopping into rectangular blocks and sawing into individual wafers. Some of the processes including patterning the wafers with a low-cost polymer, and a wet etch chemistry for texturization are proprietary while others such as diffusion and metallization/screen printing are standard. Chen et al [13] described in their paper a method that is capable of in-line monitoring of several solar cell process steps including texturing, anti reflection (AR) coating and metal contact properties. The measurement technique is said to be rapid implying savings in manufacturing costs of solar cells and wafers. Cocworth [14] has reported the contribution of a Mississippi based company called Twin Creeks in lowering the cost of crystalline silicon wafers by exfoliating a 20 micrometer-thick layer from a 3mm thick crystalline silicon disk. It is claimed that the disk can be reused up to 14 times. This is achieved by bombarding the disks with ions in a vacuum chamber. The company reasoned that production cost could be reduced by making the wafers thinner but that using the traditional production techniques would result to wafers that are too fragile to stand up to the rigours of photovoltaic panel production. The disks are transferred robotically to a heated furnace where hydrogen ions expand and the microscopic bubbles cause the top surface of the disk to peel off and is ready for use after applying a supportive metal backing. The resulting ultra-thin wafers are claimed to be at least as efficient as their thicker traditional counterparts, yet requiring 90 percent less silicon to produce and thus reducing production cost by half. In a contribution to reduce the complexity and processing time of the traditional silicon-wafer manufacturing technique, the company, Nanosolar used a process similar to offset-printing to make solar cells, Harris [15]. A printer operating in an open-air environment, deposits a thin layer of semiconducting ink onto reams of aluminium foil rolling through large presses. If the claim that the process can reduce production cost to about \$0.3/W holds, the attainment of grid parity may not be far away. Sitinger [16].has reported that studies at Fraunhofer Institute (IST) have led to the replacement of the plasma by hot wires in the deposition of silane gas on crystalline silicon. The use of hot wires has resulted in cost reduction and the consumption of up to 90% of the silane gas as against only 15% when plasma vapour is used. The overall aim is to produce devices with a low enough cost and high enough conversion efficiency that can compete with

traditional methods of generating electricity. The drive to create devices at low cost and high conversion efficiency has created considerable interest in a range of emerging laser-based manufacturing processes. Clark [17] has reported of laser doping of selective emitters in which the University of New South Wales is said to have done extensive work. This offers significantly better performance over the existing screen-printed technologies, and yet the new cells are claimed to be relatively simple and inexpensive to implement in existing production lines and the process has been shown to increase cell efficiencies in absolute terms by about 2%. Chandler [18] has reported that researchers at MIT have been able to devise a means of harnessing a broader spectrum of solar energy. It has been found in this study that the pressure exerted on a material, creates a varying strain to change the atomic structure, enough to “tune” different sections of the material to different wavelengths of light — including not just visible light, but also some of the invisible spectrum, which accounts for much of sunlight’s energy and in this way a wider spectrum solar of energy is captured Runyon [19] has described how a San Francisco based company, Soitec has achieved 43.6% cell efficiency using a proprietary technology and the company is reported to be currently working to achieve 50% by 2015 using concentrated photovoltaic (CPV) in areas of high direct normal irradiance (DNI). The innovative four-junction cell uses two new dual-junction sub cells grown on different III-V compound materials, which allows optimal band-gap combinations tailored to capture a broader range of the solar spectrum. This maximizes energy-generating efficiency. It is reported that Soitec leverages its proprietary semiconductor-bonding (Smart Stacking) and layer-transfer (Smart Cut) technologies that have been used in volume production by the global semiconductor industry for decades, to successfully stack non-lattice-matched materials while also raising the possibility of re-using expensive materials. Inexpensive large-scale production of graphene is aggressively being pursued, Amunsen and Lie [20]. Graphene possesses some beneficial properties and as a result it is considered to be the prime candidate to replace silicon. The material, graphene is one-graphite-atom thick, 200 times stronger than steel, transparent, impermeable, pliable, conducts electricity 100 times faster than silicon and is superior to any other material in conducting heat. Graphene can supplant the semiconductor substrate and serve as a transparent electrode for a pliable nanowire solar cell. Nanowires grown on graphene can be used in solar cells, where the same amount of sunlight can be converted to energy using only one-tenth the volume of materials used in thin-film solar cells. Montgomery [21] reports of four companies that are working on reducing cost by eliminating the use of most of the silicon material and related processes. Four of the companies involved work on techniques based on high-temperature (1000-1100°C) chemical vapour deposition of epitaxial silicon, a type of thin crystalline silicon that conducts both laterally and

longitudinally, unlike amorphous silicon that conducts only longitudinally. Cell efficiencies reported range from 21% by Solexel to 15% by Crystal Solar and Amber wave. The technology used by the forth company, Scifiniti creates an ultrathin layer of multicrystalline silicon on top of a lower-cost silicon substrate. The technology cuts energy use by half, reduces silicon used by more than 90% and eliminates most of the common defects.

## V. DISCUSSION

Two factors are responsible for the continual drop in the price of solar cells and these are the insecurity in the oil producing regions of the world and the penchant for utility companies to hike-up grid electricity tariff. The study has shown that the complex manufacturing process and the reluctance of manufacturers to invest in research and development were responsible for the high cost of solar cells. As long as the semiconductor and satellite industries, the main clients to the silicon manufacturers, do not complain that the cost of silicon is high there would be no incentive to invest on research and develop ways of reducing manufacturing costs. Silicon manufacturer dictate the price and the semiconductor and the satellite industries pay with no questions asked. The reluctance of the silicon industry notwithstanding, the realization of the finiteness of oil as a resource and the oil crisis of the seventies brought it home to all that there is an urgent need to find alternative energy sources. Interested research organizations and the universities took up the challenge and for quite a while have been engaged in research on how to reduce the manufacturing cost of the silicon hence solar cell. The result of these research efforts are gradually paying off. The price of solar cells is slowly but surely falling and individuals who are interested in leaving a cleaner environment for future generations and/or in being independent of the utility companies are taking advantage of the fall in price to go solar, Various government have also contributed to encourage individuals to buy into solar and other forms of renewable energy by creating incentives in the form of both subsidized installation of solar system to homes and feed in tariffs popularly known as "FITS" whereby the excess energy generated by the individual is sold to the utility companies and eventually fed into the national grid. This has had a beneficial effect – many who may not have contemplated installing solar energy system have done so and the cumulative effect is manifested in the resulting fall in prices of solar cells and this may be attributed to the economy of scale. Every nation guards its sovereignty not just at the political level but also at the economic level. Much of the interest in renewable energy including solar, can be seen as an insurance to protect non oil producing nations from the unpredictability of action by oil producers. Global warming has further accelerated action in the quest for alternative sources of energy and solar energy is a beneficiary.

## VI. CONCLUSION

1. Faster growth in the application of solar energy in terrestrial use has been hampered by the common production method used in both semiconductor and solar cell sectors.
2. Common Manufacturing methods makes it impossible to take advantage of the fact that the solar cell could tolerate some impurities in the silicon
3. Improvements in solar cell manufacturing methods, may have combined with other factors to act as the stimulant to volume use and price drop of solar cell.

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