MANUFACTURING TECHNIQUES OF LOW- COST SI-BASED CRYSTALLINE TYPE SOLAR CELL IN BANGLADESH

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Abstract: *In today's world with the increasing population, the world's energy needs are growing steadily and the crisis for power is also increasing. All the conventional sources of energy like gas, coal, oil etc are limited. In this situation, the need for establishing a renewable energy source as an alternative energy generation system has become very important for sustainable energy security of the country. Among various renewable energy sources, solar energy comprises a large portion. The solar energy captivated by Earth's atmosphere, oceans and land is about 385000 EJ[1]. But only less than 1% of useful energy comes from solar power [2]. This statistics shows that, the sun shine produces 35000 times more power on earth than the daily power production using solar energy. Thus the earth receives more energy from the sun in just one hour than the world uses in a whole year.[3] The conversion of sunlight into electricity using solar cells system (10-14%) is worthwhile way of producing this alternative energy. Bangladesh receives strong sunshine throughout the whole year (3.8-6.42 Kw-hr/m²) and it has been found that the average sunshine hours are 6.69, 6.16 and 4.81in winter, summer and monsoon, respectively.[4] Bangladesh is also adopting means to use solar energy day by day. Many private Companies in Bangladesh import solar panels from abroad and sell them into the country. The approximate cost for importing readymade panels varies from 90-98 BDT per Wp. There are some companies which import solar cells from foreign countries and assemble them into panels. The average cost for importing cells is approximately 41-57 BDT per Wp. The cost of assembled panels from imported cells is approximately 78-84 BDT per Wp. From the analysis it is found that, the cost of a locally produced PV panel is 10 percent lower than imported ones [5] because of 60% cost incurs for producing cells from raw materials. Although solar panels are being produced in Bangladesh, till now solar cells have not been fabricated yet. In Bangladesh for the first time 'Bangladesh Atomic Energy Commission (BAEC)' is going to set up a laboratory to fabricate crystalline solar cells. It is anticipated that producing cells from raw materials locally and then assembling them into PV panels will reduce the cost almost 30%. This paper explores how fabricating crystalline solar cells locally is anticipated to reduce cost of solar panels. If the cost effective technology could be made familiar in Bangladesh then it would help in solving our power crisis in a great deal.*

Key Words: *Energy crisis, solar energy scenario, assembling solar panels, cost effective solar cell fabrication.*

INTRODUCTION

The world's increasing need for energy has made it necessary that people rely on renewable energy sources rather than conventional ones. Solar energy often termed as the source of nearly all energy available on earth, is one of the major renewable energy sources and can give a solution to the present day energy crisis. The solar energy captivated by Earth's atmosphere, oceans and land is about 385000 EJ [1]. In spite of this large energy captivation, only less than 1% useful energy comes from solar power [2]. Hence, this shows the result that, the sun shine can produce about 35000 more power on earth than the daily power production using solar energy [2]. In Bangladesh the average sunshine hours are 6.69, 6.16 and 4.81in winter, summer and monsoon, respectively [4]. Photovoltaic (PV) method which converts solar radiation directly into electricity using solar cells is a simple and unique method to use solar radiation as it is non-polluting, noiseless, reliable and has a long life [6]. Solar cells are made from different semiconductor material which affects the cost and efficiency. Solar cells can be made of Crystalline Silicon which include mono crystalline Silicon, polycrystalline Silicon, amorphous Silicon, cadmium telluride, and copper Indium Selenide/Sulfide [7]. There are also thin film solar cells which include Cadmium Telluride solar cell, Copper Indium Gallium Selenide, Gallium Arsenide multi junction, Light-absorbing Dyes (DSSC), Quantum Dot Solar Cells (QDSCs), Organic/Polymer solar cells, Silicon thin films [8]. This paper aims in analyzing the cost effectiveness of crystalline type solar cell and panel manufacturing technology that is practiced in Bangladesh.

According to the continuation, **Section 2** deals with the principle upon which solar cells work.

PRINCIPLE OF SOLAR CELL OPERATION

Solar cell is an electronic device that produces electricity by directly converting energy from sunlight [6, 9]. This is the photovoltaic phenomenon of semiconductor solar cell by absorbsion of photon. The conversion of energy from sunlight is based on the p-n junction method. Crystalline type semiconductor solar cells are produced by doping with acceptor atoms to create p-type region and donors atoms to generate n-type region on semiconductor crystal lattice. Due to the rule of diffusion, the holes are diffused from the p type material and the electrons are diffused from the n type material at the p-n junction as shown in Fig 2.1.
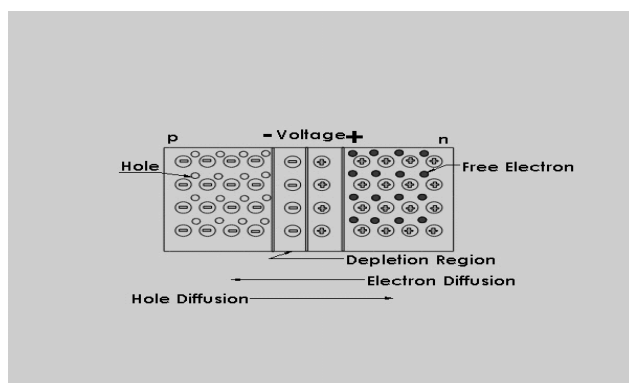

Fig 2.1: Formation of p-n Junction

According to Fig 2.1, atoms which release the electrons become positively ionized and similarly the atoms which release holes become negatively ionized. If the electrons and holes were not charged due to built in electric field, electrons and holes would continuously diffuse to the opposite direction at the junction. But in real practice, after a certain period, the next free electrons and holes coming from the remote n type and p type regions respectively are opposed by neutralized electron-hole pairs at the p-n junction. Thus a junction barrier is formed at the p-n junction which is known as the depletion region. In Fig 2.1, the depletion region is indicated at the middle. Here a minor current and a very small amount of voltage (generally 0.1-0.3V) are formed. Inspite of this, some electrons and holes pass the junction due to diffusion force. Thus they form diffusion current. On the other hand, due to the applied electric field, the electron and holes are swept across the junction and form drift current. In an open circuit solar cell, the diffusion and drift current are balanced equally. Thus the solar cell becomes electrically neutral.
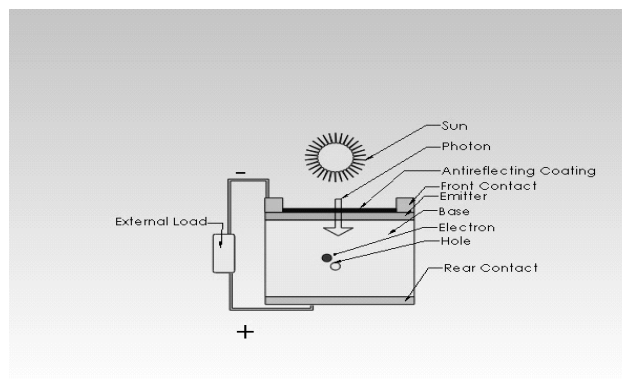

Fig 2.2: Solar Cell Operation

When the sunlight reaches the solar cell p-n junction as shown in Fig 2.2, on the way, a specific amount of incident light is reflected at the outer atmosphere and the rest portion is being transmitted through solar cell. Among these portions due to optical imperfections, phonon and other quasi-particles a fraction of light is scattered and reflected to the rear surface of the solar cell [9]. To eleminate this reflection problem Fig 2.2 shows that, an antireflecting coating is given over the front surface of solar cell which prevents reflection spectrum of the front surface. At the rear surface, there are metal coating which totally reflects back the incoming light inside the solar cell to increase the amount of photon without any absorption. The photon hits the valance electrons of the cell material atoms. These valance electrons gain energy from the photon. If this energy is enough to overcome the band gap (1.12 eV for Silicon), the electrons become free from the atom. By this process the light generated current is being induced. But due to the recombination, the light generated current and the voltage are being neutralized. Thus solar cell can not contribute to current flow. To eleminate this problem, the emitter (n-type region) and base (p-type region) are connected by wires to flow the electrons through the external circuit by creating short circuit forward bias [6]. The electrons dissipate energy to the external load while passing through the circuit and returns to the solar cell. Thus the solar cell produces voltage and supplies electricity to the external loads. The single solar cell can produce very small amount of power. That's why, a group of solar cells are combined inside a weather-tighted panel. And again a group of panels by joining with wires are involved in electricity supply projects. On the basis of this solar cell operation theory, **Section 3** gives concentration on the description of existing and cost effective technology of crystalline type solar cell fabrication.

DESCRIPTION OF EXISTING AND COST EFFECTIVE TECHNOLOGY OF

CRYSTALLINE TYPE SOLAR CELL FABRICATION

Existing Technology

Solar cells, which has become a rapidly growing and immensely important alternative to renewable energy was first practically demonstrated in 1950 [6]. Since then by using different technologies and different materials the efficiency of solar cells has increased in a great deal (14-18%). Today different technologies are used for junction formation which is basically a process of creating a new layer called 'emitter' in the substrate material. The technologies that are used for this doping method are- Phosphorus diffusion from Phosphorus Oxy-Chloride (POCl$_3$), Ortho-Phosphoric acid [10], Spin on Dopant Process, Ion Implantation, Spraying method, Epitaxy etc. [11]. Adopting different diffusion techniques affect the efficiency and cost consideration. Apart from these techniques there are also different chemical vapor deposition methods that are widely used in fabricating solar cells. They are Atmospheric Pressure Chemical Vapor Deposition (APCVD), Low Pressure Chemical Vapor Deposition (LPCVD), and Plasma Enhanced Chemical Vapor Deposition (PECVD) etc [12]. Basing on the cell fabrication technologies there are Screen Printed Solar Cells, Buried Contract Solar Cells, High Efficiency Solar Cells, Rear Contract Solar Cells [6]. In **Section 3.2** the cost effective technology is being described in details.

Cost Effective Technology

The development and implementation of different techniques and materials all these years was practiced to increase the efficiency of solar cell and to make the fabrication cost effective. Among all the methods that are practiced now-a-days it is seen that 'Spin on Dopant' and spraying method is cheaper than diffusion from a POCl$_3$ source, Epitaxy etc. Spin on Dopant is one of the most conventional diffusion processes. In this process liquid dopant solution is applied to the wafer and the wafer is spun at high speed to produce a thin film source [3]. This process is relatively cost effective due to the simplicity of the whole procedure. There is another diffusion process called 'POCl$_3$ Diffusion' which is slightly expensive than the spin on dopant process. It is mainly the use of different advanced machinery, chemicals and overall process that increase the fabrication cost. It is widely used now-a-days by the solar cell manufacturers. [10] Phosphorus is diffused from a liquid phosphorus Oxy-Chloride (POCl$_3$) source in a closed quartz tube. In this procedure double amount of samples can be processed at the same time. This large processing capability is one of the main advantages of POCl$_3$ diffusion. Another advantage of this technology is the self-governing control of the pre-deposition and the drive-in, due to which the surface source can more easily be made finite. Thus, a greater control of the surface concentration of P diffused emitters is achieved. In addition to that an extra parameter of freedom during process optimization can be obtained [10]. The carrier lifetime of multi crystalline wafers are increased tremendously in thePOCl$_3$ diffusion process as a result of impurity gettering [4]. Due to all these advantages over the Spin on Dopant process, POCl$_3$ diffusion is industrially most wide-spread method for emitter formation [8]. That is why Bangladesh Atomic Energy Commission (BAEC) has also adopted this process in their laboratory.

According to the application of metal contacts solar cell can be divided as screen printed solar cells, buried contact, high efficiency and rear contact solar cells. Among them screen printing is the simplest and most cost effective method and is going to be followed in BAEC.

The details of solar cell fabrication process using POCl$_3$ diffusion technology is described in **Section 4**.

CRYSTALLINE TYPE SOLAR CELL FABRICATION PROCESS USING POCl$_3$ DIFFUSION TECHNOLOGY

Basic Material, Chemical Components, Equipment and Machinery

Crystalline type solar cell fabrication deals with a set of basic material, chemical components and equipment and machinery.

The specifications of the basic material are stated in Table 4.1.1. The basic material [6] used for solar cell fabrication is multi crystalline type Silicon wafers that are p-type doped with small amount of Boron. The usual square shape wafer is 10×10 cm^2 in size and 0.5 mm in thickness.

Table 4.1.1: Basic Materials Involved in Solar Cell Fabrication

Material	Type	Doping	Shape	Size
Silicon Wafers	Multi Crysta-lline	P-type doped with small amount of Boron (1e16 atoms/cm^3)	Square	Starting wafer is usually about 10×10 cm^2 in size and 0.5mm thick.

Various chemical components [6] are used in solar cell fabrication. They are described in Table 4.1.2. As stated in Table 4.1.2, hot solution of Sodium Hydroxide is used during wafer texturing and to reduce saw damage of first 10µm of damaged Silicon and contamination of Silicon wafer. Isopropanol or Isopropyl Alcohol is used as a wetting agent during texturing. Sulphuric Acid and Nitric Acid neutralize the basic layers and enhance more uniform etching

across grain boundaries and remove diffusion glass after emitter diffusion. Hydrogen per Oxide is used with Sulphuric Acid to remove organic materials from the substrate. Hydrogen fluoride removes native oxide from Silicon surface. Combined with Ammonium Hydroxide, Hydrogen Fluoride (HF) is used to remove organic materials from substrate. Silane and Ammonia which are dielectric coatings enhance optical and electrical properties of solar cells by surface passivation. During pre-deposition of $POCl_3$ diffusion process nitrogen (N_2) is used as a carrier gas to bring liquid $POCl_3$ into the chamber inside the furnace. Oxygen (O_2) is supplied externally for reaction as well. Phosphorus Oxy-Chloride inserts emitter during Phosphorus diffusion. Carbon Tetra Fluoride and Oxygen are used during edge isolation to separate the front side from the rear side of the solar cell. Silver and Aluminum pastes make the electrical flow path and back surface field (BSF). Compressed air is used for handling sensitive solar cells by pneumatic machines [15]. It applies high suction force with vacuum to cushion the solar cells. It is also used for cleaning foreign particles from the solar cell surface and drying the wet solar cells.

Solar cell fabrication process requires a set of equipment like conveyor belts, wafer loaders, stainless steel cabinets etc and different machinery [6]. Wet chemical processing bench rinses the excess chemicals of the Silicon wafer. This will eliminate the contamination of chemicals over the wafer and create surface texturing. DI water plant is used to wash away further chemicals over the wafer. Centrifuge is used for the final rinse and spin dry of the wafers. $POCl_3$ Diffusion Furnace is used to diffuse phosphorus on the wafer surface. In Solar Cell Edge Isolation Machine, edge isolation is combined with the removal of the phosphor-silicate glass layer. The emitter layer produced on the backside of the wafer during the diffusion process is isolated from the front side. It is done to prevent malfunctions of the solar cell. Anti-reflection Coating System is used to produce a thin layer of dielectric material which acts as an Anti-reflection coating, with a specifically chosen thickness. Screen printers are used to provide the metal paste of aluminum or silver over the front and rear surfaces of solar cells. Driers are used to bind the metals over the Silicon and to evaporate off the organic binders in the paste at a low temperature of about 200⁰C. Heat treatment machine is used for Rapid Thermal Cooling or RTC annealing process. Solar Simulator Machine is used to measure the efficiency of solar cell. Here, light from one or more lamps (same intensity value as sun light) is incident upon cell surface and current and voltage are measured. Then the I-V characteristics of solar cell are obtained to measure the cell efficiency. Table 4.1.3 shows the name and applications of machinery involved in solar cell fabrication.

Table 4.1.2: Chemicals Incorporated with the Production of Solar Cells

| Chemical Component	Applications
Sodium Hydroxide	For wafer texturing, to reduce the saw damage of first 10μm of damaged Silicon and contamination hot solution of sodium Hydroxide is used.
Isopropanol or Isopropyl Alcohol	This alcoholic element acts as wetting agent in texturing process.
Sulphuric Acid, Nitric Acid,	These are used to neutralize the basic layer and to enhance more uniform etching across grain boundaries. Also they are used to remove the diffusion glass after emitter diffusion
Hydrogen per Oxide	Combined with Sulphuric Acid to remove organic materials from substrate.
Hydrogen Fluoride (HF)	Hydrogen Fluoride removes native oxide from Silicon surface. Combined with Ammonium Hydroxide, HF is used to remove organic materials from substrate.
Silane, Ammonia	Dielectric coatings are applied to enhance optical properties and electrical properties by surface passivation.
Nitrogen, Oxygen	During pre-deposition of $POCl_3$ diffusion process nitrogen (N_2) is used as a carrier gas to bring liquid $POCl_3$ into the chamber inside the furnace. Oxygen (O_2) is supplied externally for reaction as well.
Phosphorus Oxy-Chloride	To insert emitter during phosphorus diffusion.
Carbon Tetra Fluoride, Oxygen	In case of plasma etching during edge isolation these components are used to separate the front side from the rear side of the cell.
Silver, Aluminum	These metal wet pastes are applied to the front side and rear side of the cell to make electricity flow path and Back Surface Field (BSF).
Compressed Air	It is used for pneumatic machine operation to handle solar cells, cleaning, drying.

Table 4.1.3: Operating Machines during Solar Cell Fabrication

| Machine Name	Applications
Wet Chemical Processing Bench	To rinse excess chemical layers to eliminate contamination and to create surface texturing wet chemical processing bench is used.
DI Water Plant	DI water plant washes the rest of the chemicals.
Centrifuge	To final rinse and spin dry centrifuge is used.
$POCl_3$ Diffusion Furnace	To diffuse phosphorus on the wafer surface $POCl_3$ Diffusion Furnace is used.
Solar Cell Edge Isolation Machine	In this machine edge isolation is combined with the removal of the phosphor-silicate glass layer. The emitter layer produced on the backside of the wafer during the diffusion process is isolated from the front side. It is done to prevent malfunctions of the solar cell.
Anti-reflection Coating System	It is used to produce a thin layer of dielectric material which acts as an Anti-reflection coating, with a specifically chosen thickness.
Screen Printer	For providing metal (Silver/Aluminum) paste layers over the front and rear surfaces of solar cells.
Drier	Drier is used to bind the metals over the Silicon and to evaporate off the organic binders in the paste at a low temperature of about 200°C.
Heat Treatment Machine	For RTC Annealing Process.
Solar Simulator Machine	It is used to test the I-V characteristics of solar cell hence to measure efficiency.

Solar cell fabrication process requires a set of equipment like conveyor belts, wafer loaders, stainless steel cabinets etc and different machinery [6]. Wet chemical processing bench rinses the excess chemicals of the Silicon wafer. This will eliminate the contamination of chemicals over the wafer and create surface texturing. DI water plant is used to wash away further chemicals over the wafer. Centrifuge is used for the final rinse and spin dry of the wafers. $POCl_3$ Diffusion Furnace is used to diffuse phosphorus on the wafer surface. In Solar Cell Edge Isolation Machine, edge isolation is combined with the removal of the phosphor-silicate glass layer. The emitter layer produced on the backside of the wafer during the diffusion process is isolated from the front side. It is done to prevent malfunctions of the solar cell. Anti-reflection Coating System is used to produce a thin layer of dielectric material which acts as an Anti-reflection coating, with a specifically chosen thickness. Screen printers are used to provide the metal paste of aluminum or silver over the front and rear surfaces of solar cells. Driers are used to bind the metals over the Silicon and to evaporate off the organic binders in the paste at a low temperature of about 200°C. Heat treatment machine is used for Rapid Thermal Cooling or RTC annealing process. Solar Simulator Machine is used to measure the efficiency of solar cell. Here, light from one or more lamps (same intensity value as sun light) is incident upon cell surface and current and voltage are measured. Then the I-V characteristics of solar cell are obtained to measure the cell efficiency. Table 4.1.3 shows the name and applications of machinery involved in solar cell fabrication.

**Fabrication Process (Front End Process)**
Solar cell Fabrication process or front end process starts from the Silicon wafer processing. Flow Chart 4.2.1 briefly shows solar cell fabrication process.
Flow Chart 4.2.1 describes that, there are ten steps involved in front end process. At first the starting wafers are p type doped with small amount of Boron. The starting wafer remains uneven because of saw damage and it is coated with cutting fluid. To remove the outer layer saw damage of Silicon, a strong alkaline etch is used. $POCl_3$ diffusion if used for emitter formation. Phosphorus is diffused from liquid Phosphorus Oxy- Chloride ($POCl_3$) source in a closed quartz tube. Once the samples are loaded in the tube, the furnace is heated up to the preferred temperature before any processing can take place. During the initial stage or pre-deposition stage of the diffusion process, carrier gas nitrogen is passed to feed liquid $POCl_3$ into the process chamber. There it evaporates and reacts with externally supplied O_2 and forms P_2O_5 on the wafer surfaces, described by Eq. (1)
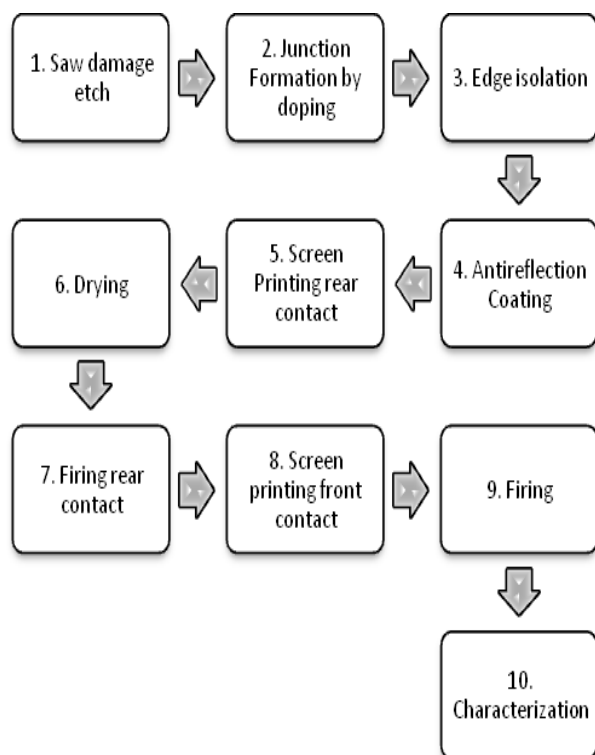
Flow Chart 4.2.1: Solar Cell Fabrication Process (Front End)

$$4POCl_3(g)+3O_2(g)= 2\ P_2O_5(l)+ 6Cl_2(g). \tag{1}$$
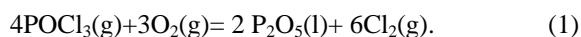
During this stage, Cl_2 (Chlorine) is constantly vented from the system. The supply of $POCl_3$ is eventually stopped to control the thickness of the growing glass. In the drive-in stage indiffusion of P (Phosphorus) from the surfaces occurs with the reduction of P_2O_5 by Si according to Eq. (2) [8]

$$2P_2O_5(l)+5Si(s)=5SiO_2(s)+4P(s). \tag{2}$$
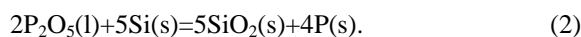
As the Phosphorus is diffused into both front and rear surfaces, edge isolation is performed to break this Phosphorus diffusion around the cell. It is commonly done by stacking the wafers above one another and using plasma etching. After this, anti reflecting coating is provided to the cell surface. Then front surface of the cell is screen printed by applying Silver paste. The wet cells can be easily smudged and thus loaded into a drier to evaporate off the organic binders in the paste. The cells are then flipped to be screen printed on the rear. The rear is printed in two parts. In the first part a thick layer of aluminum paste supplies a Back Surface Field (BSF). In the second part Silver strips are printed on the cell for afterward soldering to interconnect metal tabs [6]. Then the cells are fired at a higher temperature to remove the remaining organics and to let the silver regions to combine [16].

After finishing a complete solar cell, some characterization testes [6] are operated. These tests show how efficient the solar cell is. One of the teats is Sheet Resistivity Measurement. Sheet resistivity of solar cell top surface emitter layer is experimentally measured by using "four point probes". The outer 2 probes are supplied with current typically about 4.53 miliampere (mA) which induces a voltage in milivolt (mV) in the inner 2 probes. Current flow is kept continuous through the emitter and the p-n junction depletion layer acts as insulator. The cell is kept in dark to perform this test. Generally typical solar cell sheet resistivity lies between 30-100Ω.

Another test is performed as Contact Resistance Measurement. Contact resistance losses are observed at the places of interface between the solar cell and the metal contact. There are several methods for contact resistance measurement but biasing the solar cell is the most popular among them. In this method the cell is biased at the maximum power point and then the voltage drop along the cell is measured. This process can be automated by producing map of the cell to show the large regions of contact resistances. It is done by Resistance Analysis by Mapping of Potential (RAMP) technique.

Spectral Response Measurement is the ratio of the current generation by the solar cell to the total power incident on the solar cell (A/W). It is a graphical measurement to compare the spectral response of solar cell with the ideal cell. The wavelength is placed along the abscissa and the spectral response (A/W) is placed along the ordinate. Spectral Response (SR) measurement is important because from this, the Quantum Efficiency (QE) can be measured. Eq. (3) shows the relation between spectral response and quantum efficiency.

$$SR = \left(\frac{q \times \lambda}{h \times c}\right)QE \quad SR = \left(\frac{q \times \lambda}{h \times c}\right)QE \tag{3}$$

Here, q= Electronic Charge (1.602×10^{-19} Coulomb), λ= Wavelength, h= Plank's Constant ($6.626068 \times 10^{-34}\ m^2Kg/s$), c= Speed of Light at Vacuum (299,792,458 m/s).

Solar cell Efficiency Measurement is the most fundamental solar cell characterization technique. Efficiency is the ratio of electric power output from the solar cell to the total irradiance from sun [17]. Thus Eq. (4) shows the calculation of efficiency from the ratio of output maximum power to the input power. max oc sc

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P\ in} \quad \eta = \frac{V_{oc} \times I_{sc} \times FF}{P\ in} \tag{4}$$

Where,

$$P_{max} = V_{oc} \times I_{sc} \times FF$$
$$P_{max} = V_{oc} \times I_{sc} \times FF$$

Here, η = Efficiency, V_{oc} = Open Circuit Voltage, I_{sc} = Short Circuit Current, FF=Fill Factor, P_{in} =Input

power (Total Solar Irradiance), $Pmax$ = Maximum Power Output from Solar Cell.

To get the data for calculating efficiency from Eq. (4), IV curve supplies the required graphical value. IV curve is the current (according to ordinate) versus voltage (according to abscissa) curve. Here, the solar cell diode properties are examined as in the dark as well as in case of light generated current. From this IV curve the Open Circuit Voltage (V_{OC}), Short Circuit Current (I_{SC}), Fill Factor (FF) is being collected. To plot IV curve, the current and voltage values are collected by the technique, using IV tester. This testing machine is called Solar Simulator. One or more lamps (Intensity 1000 W/m^2) [6, 17] are set at a height as the source of light from the solar cell placed on a block. The lamps are cooled by a cooling fan. For ideal measurement condition requirements are the Air Mass 1.5 spectrum (AM 1.5), the temperature of solar cell 25°C which is kept constant by the re-circulating cooling water [6,17]. Then by measuring current and voltage, the cell efficiency is calculated.

The Bulk Lifetime (τ_b) is measured on the basis of three recombination lifetime as Radiative or Band-to-Band Lifetime (τ_{rad}), Auger Lifetime (τ_A) and Shockley–Read-Hall (SRH) Lifetime (τ_{SRH}). Eq. (5) shows the relation

$$\frac{1}{\tau_b} = \frac{1}{\tau_A} + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{SRH}}$$
$$\frac{1}{\tau_b} = \frac{1}{\tau_A} + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{SRH}} \tag{5}$$

Another Lifetime measurement is Surface Lifetime measurement. It is based on the surface recombination. The effective lifetime is measured as the combination of Bulk Lifetime and Surface Lifetime. Transient Lifetime measurement is based on the decay of the carriers over time. It is a graphical representation of light intensity versus time. The quasi-steady-state Lifetime is measured on the basis of the presence of the number of the carriers when a steady state light is incident upon a solar cell. It is performed by the graphical measurement as light intensity versus time. And the carrier lifetime is measured with Quasi Steady State Photo-Conductance (QSSPC) method by taking photo luminescence imaging of the solar cells.

After completing front end process, the back end process or assembling of solar cells to form panels is being performed step by step. The **Section 5** describes about the solar panels which are available at present market in Bangladesh and the back end process followed by the companies of Bangladesh.

ASSEMBLING SOLAR PANEL (BACK END PROCESS)

The existing solar panel producing companies of Bangladesh usually arrange panel of 24, 36, 60 and for some special cases 72 cells arrangement [18-22]. The shape of the solar cells varies as 100, 125, 150 mm round, 125mm pseudosquqre, 156mm square etc [20]. For panel with 24 mono crystalline cells arrangement, the dimension (mm) varies as 818×552×35, 890×540×35 etc with output power 50-65Wp [21-22]. For 36 cells mono crystalline panel, the dimension (mm) of each panel varies as 1200×540×35, 1196×534×35 etc for 70-90Wp output power [21-22]. For 72 cells mono crystalline panel, the available panel dimension (mm) varies like 1180×808×35, 1196×534×35, 1580×808×35 etc for 100-300Wp power output per panel [21-22]. From the statistics it is found that, in Bangladesh, on an average, the yearly production of a company is about 10 Megawatt (MW) by single shift [19].

The companies which are importing solar cells from foreign vendors follow the back end process[18] for producing solar panels. The available back end process is given as Flow Chart 5.1.
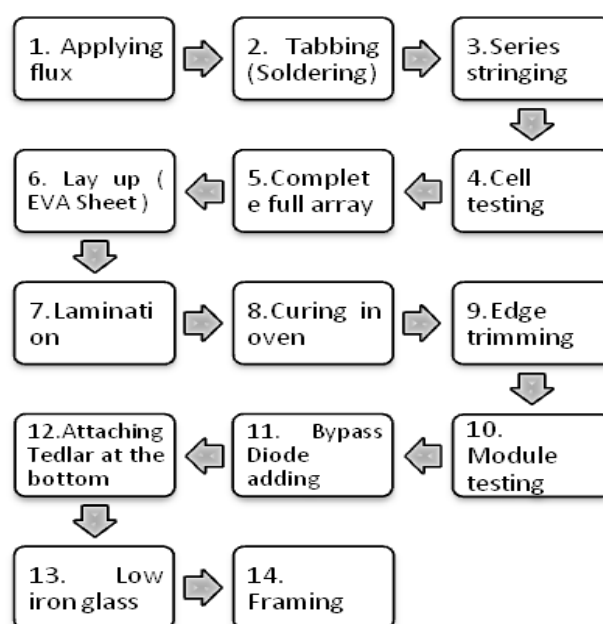
Flow Chart 5.1: Back End Process

Flow Chart 5.1 describes that there are fourteen steps involved in back end process. At first, the flux is applied over each solar cell before tabbing or soldering to avoid oxidation. Then cells are stringed in series by soldering process. At this stage, cell voltage is being tested. This voltage is found about 0.6 volt [23]. Also the efficiency of solar cells is being tested. Generally it is found that, the efficiency of 156 mm square shape solar cell varies between 4%-18% [18]. Then full cell array is completed. Lay up is done by placing Ethyl Vinyl Acetate (EVA) sheet at both the surface of cell array. Then by sending the array to lamination machine, laminating process is being completed. Then the cell array is passed to the curing oven. After that, the edges are trimmed. The panel is then brought to test inside

solar simulator [23] to measure the efficiency under Standard Test Conditions (STC) where, solar irradiation is 1000W/m², solar spectrum of Air Mass (AM) is 1.5 and module temperature is 25°C [24]. The tolerance is adopted as ±5% for the test [18]. Other Electrical characterizations include Nominal Power Calculation, Open Circuit Voltage Test, Short Circuit Current Test, Maximum Power Voltage Calculation, Maximum Power Current Calculation, Peak Power Test etc [24]. Bypass diode is then added with the arrangement [6]. Hot-spot heating occurs due to the shaded, mismatched or ineffective solar cells in the string. To eliminate this problem bypass diodes are very much effective. These bypass diodes are connected in parallel but in opposite direction of the solar cell string to create open circuit. As to attach bypass diode for each single cell is expensive so, a single diode is attached for maximum group size of 15 solar cells. At the last stage, attaching tedlar at the bottom and low iron glass on the top and final aluminum framing are done. Thus a complete solar panel is commercially produced. According to the necessity, a group of solar panels and other essential accessories are connected with wires to supply electricity.

Recently there are seven manufacturing (assembling plant) companies [19] and several other companies which are directly importing solar panels from the foreign vendors. The companies calculate the cost of solar panels according to per watt peak (Wp). **Section 6** compares the cost of solar panels between different types of companies of Bangladesh.

COST COMPARISON OF SOLAR PANELS BETWEEN DIFFERENT COMPANIES OF BANGLADESH

Cost of panels differs on the basis of imported solar cells or readymade solar panels. The cost per Wp increases much for the readymade imported solar panels than the panels produced locally from the imported solar cells. Table 6.1 compares the cost between the imported readymade solar panels and solar panels locally produced from imported solar cells[18-20].

Table 6.1: Comparison of the Cost of Solar Panels

Type of Panel	Type of Solar Cell	Cost per Wp of solar panel (BDT)
Imported readymade solar panel	Multi crystalline and mono crystalline	90-98
Solar panel locally	Mono crystalline	Around 85
produced from imported solar cells	Multi Crystalline	78-84

On the basis of these data, a result as percentage of cost efficiency of solar panels of different companies and the percentage of locally assembling costs are discussed in details in **Section 7**.

RESULTS AND DISCUSSIONS

The directly imported solar panels cost about 90-98 BDT per Wp where the panels produced from imported solar cells manufactured by the private companies of Bangladesh costs 78-84 BDT per Wp.

This statistics show that around 15% cost is reduced on the imported panel cost if the panels are produced locally with the imported solar cells. But in real practice in Bangladesh, it is observed by the companies that, the cost is reduced to 10% for locally manufactured solar panels from imported solar cells than the imported solar panels.

It costs the companies 41-57 BDT per Wp to import the solar cells only. This data shows that the companies need around 32%-47% cost to produce panel that costs 78-84 BDT per Wp.

Bangladesh Atomic Energy Commission (BAEC) has set up a laboratory to fabricate crystalline solar cells in Bangladesh. Its aim is to reduce the cost further and encourage other private sectors to involve in solar cell fabrication. It can be anticipated that if solar cells could be successfully fabricated in Bangladesh it would reduce the cost to almost 30%.

CONCLUSION

At present in Bangladesh, solar panels are directly imported from abroad and also assembled locally from imported solar cells. The cost of solar panel production is reduced if solar panels are assembled in Bangladesh comparing to that when the panels are imported from foreign countries. With the help of this scenario it can be anticipated that if the solar cells are locally fabricated, the cost of solar panels will be reduced further. The laboratory set up by Bangladesh Atomic Energy Commission (BAEC) has the aim to fabricate solar cells locally to reduce the cost even further. This will largely help in increasing the consumers of solar panels across the country. Thus many more private sectors will come forward to establish solar cell fabrication industries and will be able to keep pace with the advanced world

REFERENCES

[1]Wikipedia-SolarEnergy http://en.wikipedia.org/wiki/solar_energy
[2] Need Earth, Solar power is our free source of energy, http://www.needearth.com/ideas.jsp?s=8
[3] Need Earth, Solar power is our free source of energy, http://www.needearth.com/ideas.jsp?s=8
[4]wwwinst.eecs.berkeley.edu/~ee143/fa10/lectures/ Lec_26.pdf
[5] Rafique, S., Renewable Energy Scenario in Bangladesh: Estimation, Expectation and Future

Trend, presented and published as a Key-note country paper in WREC (World Renewable Energy Congress) VIII, Denver, Colorado, USA, Aug 29-Sept 3, 2004.

[6]http://www.thedailystar.net/newDesign/news-details.php?nid=210387

[7]Photovoltaic Education http://www.pveducation.org

[8] Mark Z. Jacobson (2009). Review of Solutions to Global Warming, Air Pollution, and Energy Security p. 4.

[9]Wikipedia-Solarcell http://en.wikipedia.org/wiki/Solar_cell

[10] Nigatu Teklu (2009) © Copyright by Nigatu Teklu 2009, Study The Effect Of Ultra Violate Radiation On Polycrystalline Silicon Solar Cell, Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Material Science, at ADDIS ABABA, ETHIOPIA march 2010.

[11] Andreas Bentzen, University Of Oslo, "Phosphorus diffusion and gettering in Silicon solar cells".

[12] Ferrada Martinez, Pablo, Diffusion through Oxide Barriers for Solar Cell Applications, 2012-06-13,http://nbn-resolving.de/urn:nbn:de:bsz:352-196190

[13] http://www.crystec.com/tridepe.htm

[14] Spin-on dopant method, United States Patent by Bruce H. Justice, Robert F. Aycock.

[15] J. Lossen, L. Mittelstädt, S. Dauwe, K. Lauer, C. Beneking. Making Use of Silicon wafers with Low Lifetimes by Adequate POCl$_3$ Diffusion. 20th European Photovolatic Solar Energy Conference and Exhibition, Barcelona, Spain, 6-10, 2005.

[16] www.festo.be/nl

[17] Crystalline Solar Cell by Martina A. Green, Photovoltaics Special Research Centre, University of New South Wales, Sydney, N.S.W Australia.

[18]Keith Emery, Measurement and Characterization of Solar Cell and Module, national Renewable Energy Laboratory, Golden, CO, USA

[19] Radiant Power, Bangladesh.

[20]Electro Solar Power Ltd, Bangladesh. www.electrosolarbd.com

[21] Rahimafrooz Renewable Energy Ltd (RRE), Bangladesh.

[22]AVA Renewable Energy Ltd. www.avasolarbd.com

[23] Greenfinity energy ltd. www.greenfinitybd.com

[24]"How It's Made-Solar Panel" by http://www.earth4energy.org on www.youtube.com/watch?v=qYeynLy6pj8

[25]Wikipedia-Solar Panel. http://en.wikipedia.org/wiki/Solar_panel#Module_perfo rmance

NOMENCLATURE

Symbol	Meaning
AM	Air Mass spectrum
APCVD	Atmospheric Pressure Chemical Vapor Deposition
BDT	Bangladeshi Taka (TK)
BSF	Back Surface Field
c	Speed of Light (m/s)
EJ	Exajoule
FF	Fill Factor
h	Plank's Constant (m^2Kg/s)
hr	Hour
I_{SC}	Short Circuit Current (Ampere)
Kw	Kilowatt
LPCVD	Low Pressure Chemical Vapor Deposition
m	Meter
mA	miliampere
mV	milivolt
P_2O_5	Phosphorus Penta Oxide
PECVD	Plasma Enhanced Chemical Vapor Deposition
$POCl_3$	Phosphorus Oxy Chloride
PV	Photovoltaic
P_{in}	Input Total Solar irradiance (Watt)
P_{max}	Maximum Output from Solar Cell (Watt)
q	Electronic Charge (Coulomb)
QE	Quantum Efficiency (%)
RAMP	Resistance Analysis by Mapping of Potential
RTC	Rapid Thermal Cooling
SiO_2	Silicon Dioxide
SR	Spectral response
SRH	Shockley –Read-Hall
STC	Standard Test Condition (STC)
V_{OC}	Open Circuit Voltage (Volt)
W	Watt
Wp	Watt peak
λ	Wavelength (m)
η	Efficiency of Solar Cell (%)
τ_A	Auger Lifetime
τ_b	Bulk Lifetime
τ_{rad}	Band-to-Band Lifetime
τ_{SRH}	Shockley –Read-Hall (SRH) Lifetime
Ω	Resistance (Ohm)