









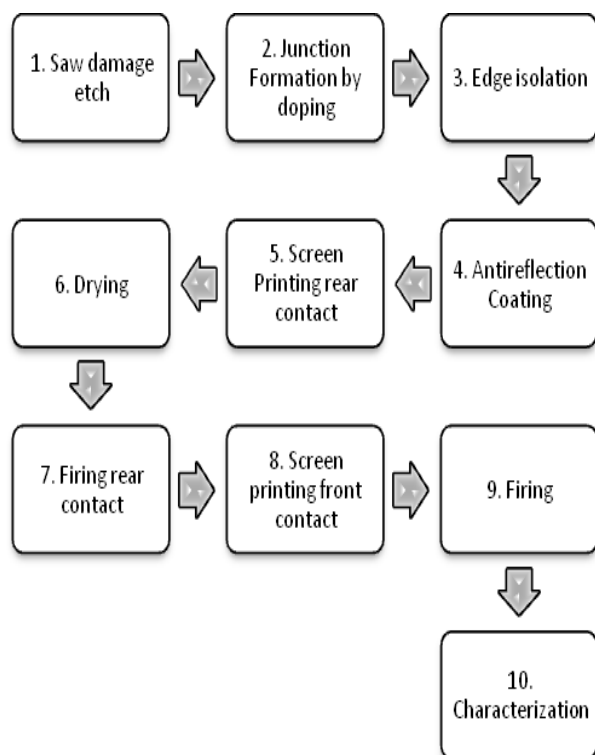
**Table 4.1.3: Operating Machines during Solar Cell Fabrication**

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 <sub>3</sub> Diffusion Furnace	To diffuse phosphorus on the wafer surface POCl <sub>3</sub> 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.

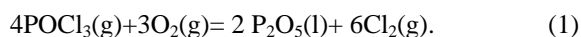
Solar cell fabrication process requires a set of equipment like conveyor belts, wafer loaders, stainless steel cabinets etc and different machinery [6]. Wet chemical processing bench rinses the excess chemicals of the Silicon wafer. This will eliminate the contamination of chemicals over the wafer and 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<sub>3</sub> 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)**

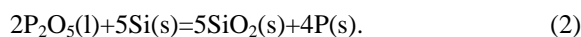
Solar cell Fabrication process or front end process starts from the Silicon wafer processing. Flow Chart 4.2.1 briefly shows solar cell fabrication process. Flow Chart 4.2.1 describes that, there are ten steps involved in front end process. At first the starting wafers are p type doped with small amount 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<sub>3</sub> diffusion is used for emitter formation. Phosphorus is diffused from liquid Phosphorus Oxy- Chloride (POCl<sub>3</sub>) 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<sub>3</sub> into the process chamber. There it evaporates and reacts with externally supplied O<sub>2</sub> and forms P<sub>2</sub>O<sub>5</sub> on the wafer surfaces, described by Eq. (1)



Flow Chart 4.2.1: Solar Cell Fabrication Process (Front End)



During this stage,  $\text{Cl}_2$  (Chlorine) is constantly vented from the system. The supply of  $\text{POCl}_3$  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  $\text{P}_2\text{O}_5$  by Si according to Eq. (2) [8]



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 tests

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 milliampere (mA) which induces a voltage in millivolt (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 30-100 $\Omega$ .

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.

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

Here,  $q$  = Electronic Charge ( $1.602 \times 10^{-19}$  Coulomb),  $\lambda$  = Wavelength,  $h$  = Plank's Constant ( $6.626068 \times 10^{-34}$   $\text{m}^2\text{Kg/s}$ ),  $c$  = 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.  $\text{max oc sc}$

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \quad \eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \quad (4)$$

Where,

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

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

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

power (Total Solar Irradiance),  $P_{max}$  = 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  $1000 \text{ W/m}^2$ ) [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  $25^\circ\text{C}$  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 ( $\tau_b$ ) is measured on the basis of three recombination lifetime as Radiative or Band-to-Band Lifetime ( $\tau_{rad}$ ), Auger Lifetime ( $\tau_A$ ) and Shockley–Read–Hall (SRH) Lifetime ( $\tau_{SRH}$ ). Eq. (5) shows the relation

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

$$\frac{1}{\tau_b} = \frac{1}{\tau_A} + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{SRH}} \quad (5)$$

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.

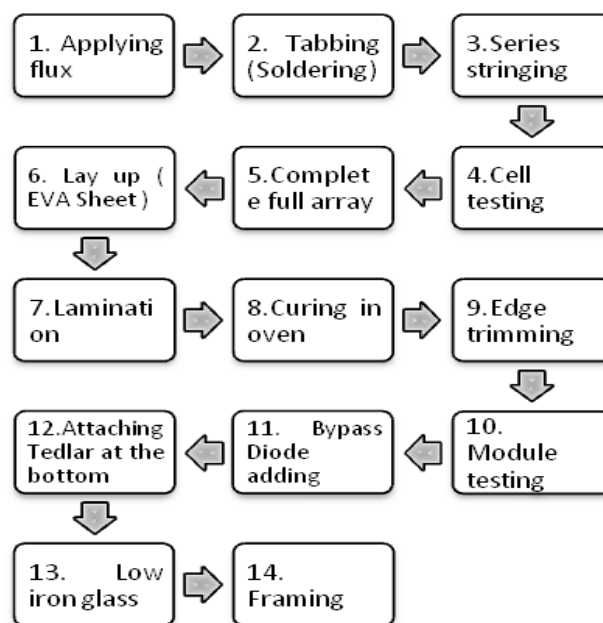
After completing front end process, the back end process or assembling of solar cells to form panels is being performed step by step. The **Section 5** describes about the solar panels which are available at present market in Bangladesh and the back end process followed by the companies of Bangladesh.

#### 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 pseudosquare, 156mm square etc [20]. For panel with 24 mono crystalline cells arrangement, the dimension (mm) varies as  $818 \times 552 \times 35$ ,  $890 \times 540 \times 35$  etc with output power 50-65Wp [21-22]. For 36 cells mono crystalline panel, the dimension (mm) of each panel varies as  $1200 \times 540 \times 35$ ,  $1196 \times 534 \times 35$  etc for 70-90Wp output power [21-22]. For 72 cells mono crystalline panel, the available panel dimension (mm) varies like  $1180 \times 808 \times 35$ ,  $1196 \times 534 \times 35$ ,  $1580 \times 808 \times 35$  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  $1000\text{W/m}^2$ , solar spectrum of Air Mass (AM) is 1.5 and module temperature is  $25^\circ\text{C}$  [24]. The tolerance is adopted as  $\pm 5\%$  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 produced from imported solar cells	Mono crystalline	Around 85
	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

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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 <sup>2</sup> Kg/s)
hr	Hour
I <sub>sc</sub>	Short Circuit Current (Ampere)
Kw	Kilowatt
LPCVD	Low Pressure Chemical Vapor Deposition
m	Meter
mA	milliampere
mV	milivolt
P <sub>2</sub> O <sub>5</sub>	Phosphorus Penta Oxide
PECVD	Plasma Enhanced Chemical Vapor Deposition
POCl <sub>3</sub>	Phosphorus Oxy Chloride
PV	Photovoltaic
P <sub>in</sub>	Input Total Solar irradiance (Watt)
P <sub>max</sub>	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 <sub>2</sub>	Silicon Dioxide
SR	Spectral response
SRH	Shockley –Read-Hall
STC	Standard Test Condition (STC)
V <sub>oc</sub>	Open Circuit Voltage (Volt)
W	Watt
W <sub>p</sub>	Watt peak
λ	Wavelength (m)
η	Efficiency of Solar Cell (%)
τ <sub>A</sub>	Auger Lifetime
τ <sub>b</sub>	Bulk Lifetime
τ <sub>rad</sub>	Band-to-Band Lifetime
τ <sub>SRH</sub>	Shockley –Read-Hall (SRH) Lifetime
Ω	Resistance (Ohm)

## NOMENCLATURE