# Challenges and Prospects of Cost-Effective Si-based Solar Cells Fabrication in Bangladesh

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***Abstract*—Solar cells are the basic building blocks of Solar Panels or Modules. There are presently nine companies manufacturing solar modules in the country. The total demand for solar cells in assembling solar modules of the nine companies are about 80-90MWp annually. In assembling solar modules, major raw materials include finished solar cells, bus bars, EVA, Al frame, tempered glass etc. All of them are import dependent for the case of Bangladesh. It is found that about 55-60% of total panel/module cost depends on solar cells. Cost-effective power generation using solar module solely depends on the quality of solar cells. Now-a-days, cost of solar cells has been decreasing rapidly over the last 3-4 years due to large scale production plants, technological improvement, declining cost of raw materials and competitiveness in the global markets. Solar cells which were used to sell for USD2.5 per Wp can be bought on a commercial scale for around USD1.2 per Wp. Mainly, cost of solar cell depends on the Brand, type of crystal structure (Mono or Multi) and the shape or size of wafer. For the first time in the country, 'Bangladesh Atomic Energy Commission (BAEC)' has set up a laboratory to fabricate crystalline solar cells on a pilot basis. The method used to fabricate solar cells is the low-cost diffusion technique using $POCl_3$ gas source. Several solar cells of 150×150 mm$^2$ sizes and 200 micrometer thick are produced and characterized in the laboratory. The results have shown us some challenges and good potentialities in getting the high-efficient and cost effective solar cells. The paper addresses the challenges and potentialities in fabricating the quality based crystalline solar cells using slightly p-doped Si-wafers and chemicals in order to adopt technology so as to reduce the cost of solar modules. If the cost effective technology can be made familiar in Bangladesh then it will help in solving the power crisis in the country a great deal.**

***Keywords*—Solar cell fabrication; cell efficiency; cost effictiveness; energy crisis***

## I. Introduction

The world's increasing need for energy has made it necessary that people rely on renewable energy sources rather than conventional one. 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 means the sun shine can produce about 35000 times more power on the earth than the daily power generation using solar energy. In Bangladesh, the average sunshine hours are 6.69, 6.16 and 4.81 in winter, summer and monsoon, respectively. 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 noiseless, reliable and has a long life. Solar cells are made from different semiconductor materials which affect the cost and efficiency. Solar cells can be made of crystalline silicon, called Generation-I which includes mono-crystalline silicon, polycrystalline silicon, amorphous cadmium telluride, and copper indium selenide/sulfide [7]. There are also thin film solar cells, called Generation-II which includes cadmium telluride solar cell, copper indium gallium selenide, gallium arsenide junction, light-absorbing dyes (DSSC), quantum dot solar cells (QDSCs), organic/polymer solar cells, silicon thin films [8]. The paper aims in analyzing the manufacturing processes that is practiced in the laboratory with an aim to developing cost-effective crystalline solar cell. Sect. II deals with the principle how solar cell works.

## II. Principle of Operation of Solar Cell

*Solar cell is an electronic device that produces electricity by directly converting energy from sunlight. This is the photovoltaic phenomenon of semiconductor. 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 1.* According to Fig. 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.

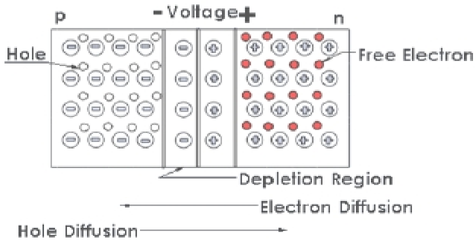


Fig. 1: Formation of p-n Junction

Thus a junction barrier is formed at the p--n junction which is known as the depletion region. In Fig.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. In spite 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. When the sunlight reaches the solar cell pp-n junction 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] that, an anti-reflecting coating is given over the front surface of solar cell which prevents reflection spectrum of the front surface. At the rear surface, there is 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 cannot contribute to current flow. To eliminate 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 is why, a group of solar cells are combined inside a weather-tighten 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, Sect. III describes the existing and cost effective technology of crystalline solar cell fabrication process.

## III. LOW COST SI-BASED SOLAR CELL METHOD

### *A. 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 (14-18%) has increased in a great deal. 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]. Based on the cell fabrication technologies, there are screen printed solar cells, buried contract solar cells, high efficiency solar cells, and rear contract solar cells [6]. In Sub Section B of Sect. III, the cost effective technology is described in details.

### *B. Cost Effective Technology*

The development and implementation of different techniques and materials all these years was practiced to increase the efficiency of solar cells and to make the fabrication cost effective. Among all the methods that are practiced now-a-days it is seen that ‘Spin on Doping’ and spraying method is cheaper than diffusion from a $POCl_3$ source, Epitaxy etc. Spin on Doping 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 [13]. 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 doping 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 $POCl_3$ gas diffusion source. 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 the $POCl_3$ diffusion process as a result of impurity gathering [14]. Due to all these advantages over the Spin on Doping process, $POCl_3$ diffusion is industrially most wide-spread method for emitter formation [8]. This is why BAEC has adopted this process in their newly established Solar Cell Fabrication Library (SCFL) under the project on “Solar Energy Utilization and

Development of Related Technology". Fig.2 shows the actual view of the overall laboratory set up of the SCFL.


Fig. 2: Solar Cell Fabrication Laboratory (SCFL)

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 the most cost effective method and is going to be followed in BAEC. The details of solar cell fabrication process using $POCl_3$ diffusion technology in SCFL is described in the following Sub Sect. C.

*C. Solar Cell Fabrication Process using $POCL_3$ Diffusion Gas Source*

Mono crystalline type solar cell fabrication deals with a set of basic material, chemical components and equipment and machinery. The specifications of the basic materials are stated in Table 1. The basic material [6] used for solar cell fabrication is mono crystalline type silicon wafers that are p-type doped initially. The usual square shape wafer is 150×150 $mm^2$ in size and 200µm in thickness.

Table 1: Basic Materials Involved in Solar Cell Fabrication

| Raw material | Cell type | Doping | Shape & Size | Thickness |
|---|---|---|---|---|
| Silicon wafer | Mono-crystalline | P type | 150×150 $mm^2$ | 200µm |

solar cell fabrication process which means the front end process starts from the silicon wafer processing. Fig. 3 shows the flow chart that briefly describes about the front-end solar cell fabrication processing steps. 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 (NaOH, KOH) etch is used. Figs. 4 and 5 show the wafer cleaning and texturing processes performed during cell fabrication in wet benching machine.

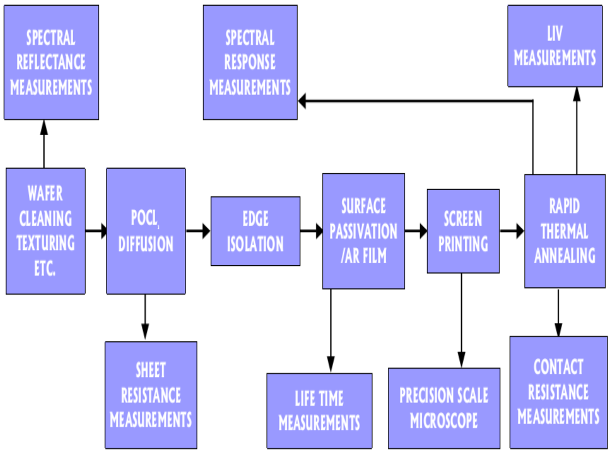


Fig. 3: Flow chart of solar cell fabrication (Frond end process) processing steps adopted in SCFL

Fig. 4: Si wafer cleaning and texturing process performed at SCFL

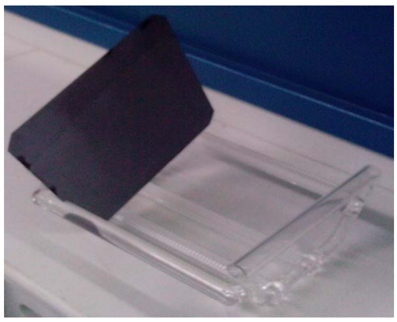

Fig 5: Si wafer after cleaning and texturing

As phosphorus is diffused into both front and rear surfaces, edge isolation is performed to separate the continuity by using EDGE isolation paste around the cell. Fig. 6 shows the edge isolated Si-wafer done mechanically by screen printer.

$POCl_3$ diffusion is used for emitter formation. Phosphorus is diffused from liquid Phosphorus Oxy-Chloride ($POCl_3$) source in a closed quartz tube.

Fig 6: Edge isolated Si wafer

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.

Fig 7: Phosphorous doped on P type Si wafer from diffusion chamber

There it evaporates and reacts with externally supplied $O_2$ and forms $P_2O_5$ on the wafer surfaces, described in the following Eq. (1).

$$4\,POCl_3\,(g) + 3O_2\,(g) = 2\,P_2O_5\,(l) + 6Cl_2(g) \tag{1}$$

After this, anti reflecting coating is provided to the cell surface. The phosphorous doped on p type Si wafer from diffusion chamber is shown in Fig. 7. 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. Fig.8 shows the front surface screen printed Si solar cell. The cells are then flipped to be screen printed on the rear. The rear surface is printed using Al paste.

Fig 8: Screen printed finished type Si wafer

The cells are then fired at different higher temperatures in three zones consecutively to form the Ohmic-contact between conductor (Al & Ag) and semi-conductor (P type & N type). Fig.9 shows the contact firing process of screen printed Si solar cell.

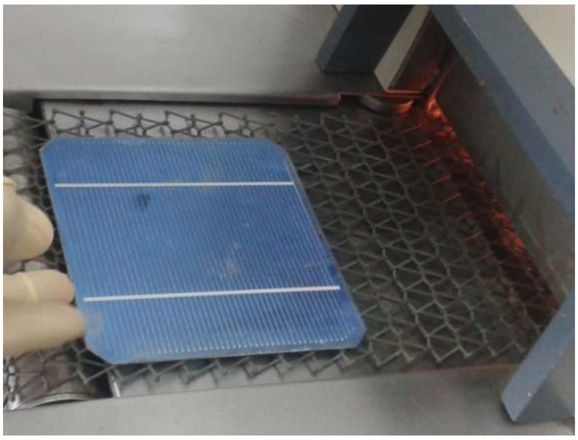

Fig 9: Contact firing at RTC furnace

## IV. Efficiency Calculation

After finishing a complete solar cell, some characterization tests [6] are carried out. These tests show how efficient the solar cell is. The major characterization equipment is LIV tester which gives the reading of open circuit voltage (Voc), short circuit current (Isc) and Fill factor (FF). These data are required to calculate the efficiency of a solar cell from the ratio of output maximum power to the input power.

Eq.2 shows the calculation of efficiency from the ratio of output maximum power to the input power.

$$\left[\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}\right] \ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots(2)$$

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

Fig. 10 LIV tester in SCFL

Fig.10 shows the LIV tester in SCFL. Solar cells are tested under one-sun conditions using Xenon-arc lamps; a Xenon spectrum is closest to the sunlight. Data acquisition based on programmable current-voltage source power supplies capable of handling currents up to 8A is used in conjunction with a proprietary data acquisition system. Calibration of this LIV measurements system is based on independently measured c-Si solar cells at Sandia National Laboratories. The measured LIV data are shown in Fig.11.

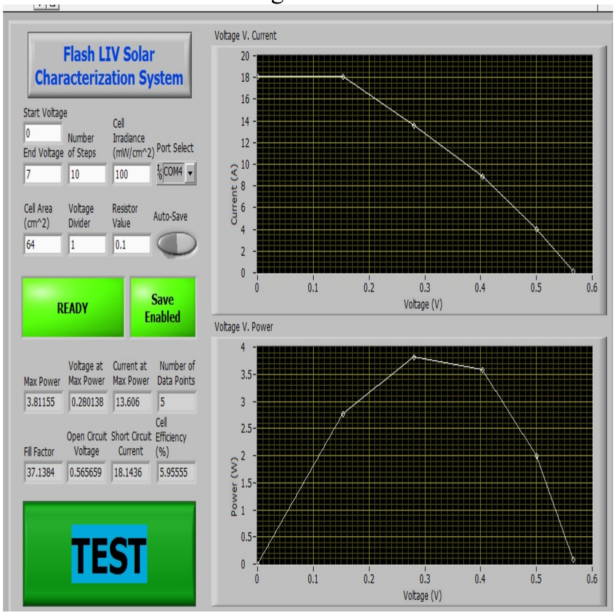


Fig. 11 Measured LIV data at SCFL

Fig. 11 shows the measured LIV data at SCFL. It gives the VI curve and the efficiency of the fabricated solar cell. From Fig. 11 it is noted that the efficiency of the produced solar cells were approximately 5.95% at the present condition. Optimizing the processing techniques as well as the air quality, water quality and other chemicals, it is very much potential to raise the efficiency of the solar cell by more than 12%.

## V. COST SCENARIO

The cost of solar cell mainly depends on the quality of cell material, cell thickness, cell area, cell efficiency, life time, brand and origin of the country. Now-a-days laboratory based Si solar cell efficiencies has been reached up to 24.7% whereas at the end of the $20^{th}$ century it was struggling in the range of 12–15%. Laboratory based solar cells are basically research grade wafer which are too expensive. At the same time, industrial scale solar cells have low price having low efficiency level (12-14%). On a positive note, the PV market, which grew at an average rate of 13% per year during 1982-1996, exploded with an average annual growth rate of 30–35% per year during 1996–2002 [25] and its advantage is the significant cost reduction due to increased production volume. Presently, there is no solar cell fabrication company in Bangladesh but nine companies which basically imports solar cells from foreign countries and assemble them into panel. Almost all of the companies import low cost & low efficiency graded solar cells and the average cost of those solar cells is 41-57 BDT per $W_p$ [26]. This shows that the cost varies in the range of 3-14% from company to company in Bangladesh. It is found that cost of the imported solar panels is higher as well as lower quality rather than locally assembled solar panels.

## VI. CONCLUSION

For the first time, a laboratory has been set up by BAEC to fabricate the commercial grade solar cell locally to reduce the cost from the imported one. To doing so, there are lots of challenges. There are different recipes and techniques available in processing solar cells. Of them, a relatively better process is established to improve the efficiency of solar cells. Efficiency varies significantly from one recipe to another and performance indicators. The main challenges are to find out the right recipe and technique which needs iterative methods. Completion of a particular recipe and technique takes 3-4 days and usages lots of consumables (raw materials, chemicals, gases etc). In summary, significant progress has been made in understanding and fabricating a wide range of silicon solar cells with the highest device conversion efficiency of 5.95%. For instance, cleaning and texturing process, optimum flow rate for $POCl_3$ and fixing the different temperature zones of RTA process is achieved which can significantly enhance the solar cell efficiency. Moreover the technology roadmap shows that cost reduction can be achieved with better back surface passivation, improved screen printing, improved surface texturing process and improve the edge isolation technique. Moreover, doping concentrations have to be further optimized and carefully characterized to get more improvement. In the near future, optimizing all the challenges the laboratory will play a pioneer role to developing as well as promoting solar cell fabrication technology in the country.

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