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Fabrication of Monocrystalline Silicon Solar Cell using Phosphorous Diffusion Technique

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Abstract- This paper gives an overview of the materials and methods used for fabricating a monocrystalline silicon solar cell. The aim of this research is to study the solar cell fabrication technology and fabrication of monocrystalline silicon solar using phosphorous diffusion technique locally. For solar cell fabrication we have used several number of processing steps to get the final solar cell output. At first we took a p-type monocrystalline silicon wafer with square shape 150×150 mm^2 in size, 200μm in thickness and which is a (100) oriented Czochralski Si wafer. Then Cleaning and texturing of the wafer was done using different chemical solutions and edge isolation of wafer was done using edge isolation paste. Phosphorous diffusion was done by diffusion furnace to form p-n junction using liquid Phosphorus Oxychloride ($POCl_3$). Front and back side metallization was done by screen printers using silver paste and aluminum paste respectively. Then Rapid Thermal Annealing of the wafer was done at high zone temperature for curing the contact. Finally, fabricated solar cell was characterized by LIV tester. LIV data shows that maximum power is 10.3369W, voltage at maximum power is 0.27504V, current at maximum power is 37.5833mA, open circuit voltage is 0.555462V, short circuit current is 56.5867mA, fill factor is 32.8868 and the efficiency of the cell is about 7%. The efficiency of our fabricated solar cell is quite low since fabrication of monocrysralline solar cell is for the first time in Bangladesh. Bangladesh Atomic Energy Commission (BAEC) has established a laboratory to fabricate solar cell locally. Optimization of processing techniques, equipment temperatures as well as the air quality, water quality and other chemicals are needed to increase the efficiency of solar cell.

Index Terms- LIV tester, phosphorus oxychloride, rapid thermal annealing, screen printing, Texturing.

I. Introduction

Electricity is a prerequisite for economic growth and social development. But Bangladesh is one of the most electricity deprived nations in the world [1], [2]. Bangladesh has been facing a power crisis for about a decade, mainly because of inadequate power generation capacity compared with demand and the aged infrastructure of many existing power generation facilities [3]. Despite the large potential for renewable energy sources in Bangladesh, currently their contribution to the electricity supply remains insignificant. Renewable energy sources in Bangladesh, particularly solar energy, can play a significant role to meet the electricity demands in the rural and remote areas of the country since around 70% of people having lack accesses to electricity and most of them are living in the village. The location of Bangladesh is ideal for tapping solar energy effectively. Sunlight is dropped in Bangladesh about seventy percent [4]. Daily solar irradiation intensity varies from 3 to 6.5kW/m^2, with a maximum during March-April and a minimum in December-January [5], [6], [7]. Crystalline silicon solar cells are used in the largest quantity of all types of solar cells on the market, representing about 90% of the world total solar cell production in 2008 [8]. Monocrystalline silicon technique is used as a promising method for solar cell fabrication [9]. For monocrystalline silicon solar cell fabrication, phosphorous diffusion technique is the most widely used technique for photovoltaic industry [10]. For the first time Bangladesh Atomic Energy Commission (BAEC) has established a monocrystalline silicon solar cell fabrication laboratory as partial fulfillment of national electricity demand. We have done our experiment in this solar cell fabrication laboratory. The current study will focus on the fabrication of monocrystalline silicon solar cell using phosphorous diffusion technique and characterization of this solar cell locally. It is expected that the development of solar cell locally will play an important role in renewable energy sector in Bangladesh.

II. THEORY OF PHOSPHORUS DIFFUSION

Phosphorus (P) diffusion is currently the primary method for emitter fabrication in silicon (Si) solar cell processing [11]. The thermal diffusion of phosphorus is necessary to create an n-type emitter to the p-type wafer [12]. The diffusion depends on various factors of which temperature and gaseous environment is most important [13]. P-type silicon wafers are widely used in solar industries and therefore diffusion technologies have been developed to deposit n-type doping elements to create the p-n junction. Along with nitrogen (N_2) and oxygen (O_2) gases, phosphorus oxychloride ($POCl_3$), a liquid source of phosphorus is also widely used in the standard diffusion process of solar cells [14], [15]. Due to its low boiling temperature (105.8 ˚C) [16], at temperatures between 850-900 ˚C in the diffusion chamber, $POCl_3$ is decomposed into simple phosphorus compounds like P_4, P_8, P_2O_5, etc. In oxygen environment and at 850°C temperature, the diffusion coefficient (D) can be approximated as D~0.0013μm^2/hr. The phosphorus diffusion fabrication of crystalline silicon solar cell with emitter diffusion, surface passivation and screen printing of electrode leads to formation of n+ type emitter at the top surface of the wafer. Phosphorus oxychloride ($POCl_3$) is a liquid source which vaporizes at room temperature itself hence it should be kept in cool place. For the diffusion process, the vapors are carried out by the carrier nitrogen and oxygen is passed through another valve. The reaction takes place, the phosphorus oxychloride reacts with oxygen forms phosphorus pentoxide and then the phosphorus pen oxide reacts with the silicon to give the silicon dioxide and the phosphorus. Generally, phosphorous diffusion process is performed in two steps. The first step is called pre-deposition that involves the formation of phosphorous-rich oxide films on the silicon substrate. Second step is called drive-in [17], [18], [19] which the phosphorous-rich oxide film acts as an infinite source for phosphorous diffusion into the Si substrate. During pre-deposition, phosphorus pentoxide (P_2O_5) forms on the surface of the wafers by the reaction of phosphorous with oxygen. The P_2O_5 immediately reacts with the silicon, by resulting in diffusion of phosphorus and formation of the phosphosilicate glass (PSG) [SiO_2: $(P_2O_5)_x$] layer on the Si surface [20]. The phosphorus atoms formed at the PSG-Si interface penetrate through the silicon wafer [21] and can be simplified with the following reaction equations:

$POCl_3$ (liquid) + N_2 (bubble) → $POCl_3$ (vapor) (pre-deposition)
4 $POCl_3$ + 3O2 →2 $P_2O_5$5 + 6Cl2
2 P_2O_5 + 5Si →4P + SiO_2 (drive-in)
P + 3Si → n-type doped Si

III. FABRICATION OF MONOCRYSTALLINE SILICON SOLAR CELL

Monocrystalline type silicon 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 [22] used for solar cell fabrication is mono crystalline type silicon wafers that are p type doped initially. Fabrication of our c-Si solar cell starts with square shape wafer of 150×150 mm^2 in size and 200μm in thickness, (100) oriented Czochralski Si (or Cz-Si) wafer.

Table 1: Basic Materials Involved in Solar Cell Fabrication

Raw Wafer	Cell type	Doping	Shape and size	Thickness
Silicon wafer	Monocrystalline	p-type	150×150 mm^2	200μm

Fabrication of monocrystalline silicon solar cell from p-type silicon wafer requires several number of process steps to get the final solar cell output. Figure 1 shows the sequence of the solar cell fabrication processing steps.

Cleaning & Texturing
Edge Isolation (Screen Printing)
POCl3 diffusion
Back metallization (Screen Printing)
Front metallization (Screen Printing)
Drying
Rapid Thermal Annealing
LIV Testing

Figure 1: Sequence of the solar cell fabrication process steps.

The starting p-type monocrystalline silicon wafer for solar cell fabrication in our experiment is shown in Figure 2. Solar cell fabrication process description in our experiments is given below.

Figure 2: Starting p-type monocrystalline silicon wafer

A. Cleaning and Texturing

Solar cell fabrication requires cleaning and texturing of wafers. Cleaning is done for the removal of the organic contaminants, thin oxide layer, and metal particles and texturing is done to create random, sub-wavelength pyramid features on wafer surface to reduce reflection and enhance light absorption [12], [23]. This kind of processing requires wet-chemical processing benches, exhaust system and water treatment prior to discharge to the waste stream. Cleaning and texturing of wafer is done by three processes which are described below.

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A.1 Saw damage removal process

At first a tray on which the wafers are kept is washed using DI water (De-ionized). A beaker is taken and it is cleaned properly using detergent and DI water. Then 4 liters of DI water is transferred to that clean beaker and the beaker is placed on a heating system and the water is heated to 70°C. Then 400 grams of sodium hydroxide pellet (NaOH) is weighted on an electronic balance and then transferred to the beaker containing DI water. The above preparation is done to make 10% NaOH solution. This has to be prepared according to the ratio, NaOH (Sodium Hydroxide): H_2O (DI-water) =1 gram: 10 ml. Once the temperature of the NaOH solution reaches 70°C which is measured using a thermometer, the tray containing the wafers is transferred to that beaker and it is dipped in that solution for 10 minutes. After 10 minutes the tray containing the wafer is removed from the beaker and then it is dipped in DI water for few times and then the wafers is ready for the next step.

A.2 Hydrophobic process

Hydrophobic process requires the preparation of a solution according to the ratio of, HF (Hydrofluoric Acid): H_2O (DI-water) = 1 ml: 50 ml. The two liquids are mixed according to the ratio mentioned above. Once the solution is prepared the wafers which went through the saw damage removal process is dipped into this HF solution for 3 minutes and then they are removed from the HF solution and dipped few times in DI-water. After that the wafers are dried using compressed air so that they are prepared for the next step.

A.3 Texturing Process

Texturing process requires preparation of a solution using the ratio of, KOH (Potassium Hydroxide): IPA (Isopropyl Alcohol): H2O (DI-water) = 1 gram: 5 ml: 125 ml. Initially we wash the beaker with DI-water and then 4 liters of DI-water is added and the beaker is placed on an electronic heater. Then 32 gram of potassium hydroxide pellet is measured on an electronic balance and then transferred to the beaker containing DI-water. When the temperature of the beaker reached 70 °C the boat containing the wafers after the HF process is placed into the beaker and then 160 ml of Iso-2-Propanol solution is added to the beaker and the wafers are kept in that solution for 10 minutes. After that the tray containing the wafers are removed from the beaker and then dipped few times in DI-water. Then the hydrophobic process is repeated and finally the wafers are dried using the compressed air and that concludes the texturing process. Then the wafer can be viewed under Scanning Electron Microscope (SEM) to see the change of wafer orientation after texturing is done. Figure 3 shows the textured silicon wafers and Figure 4 shows the Scanning Electron Microscope (SEM) pictures of textured surface of p-type silicon wafer.

B. Edge Isolation

A critical step in solar cell fabrication is electrical isolation of n and p type regions. Edge isolation is done to separate front side and back side. In the next step after wafer cleaning and texturing, back side of the wafer edge is masked using a screen printing machine and a diffusion barrier paste is used to isolate the edge. After the screen printing is done the wafers are dried for 10 minutes in a preheated oven at 200 °C. Figure 5 shows the picture of screen printer used for edge isolation and Figure 6 shows the designed screen used in our experiment.

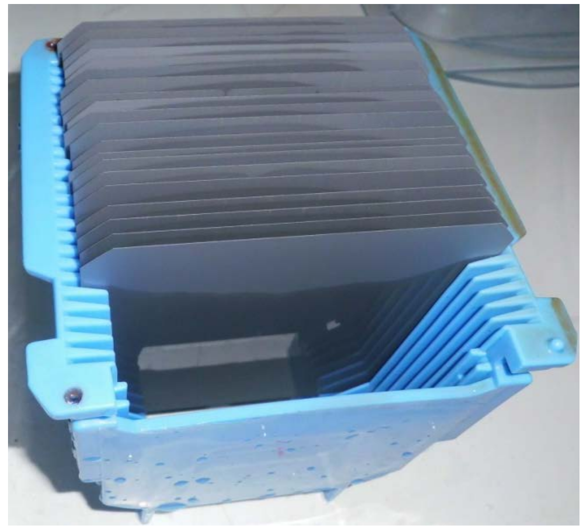

Figure 3: Textured silicon wafer

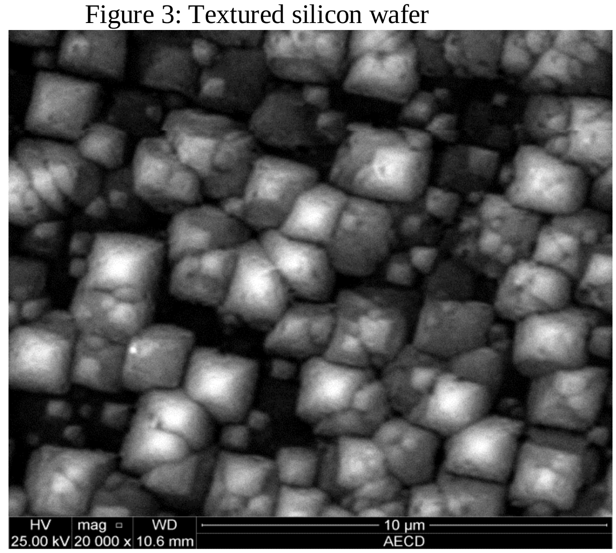

Figure 4: SEM pictures of textured silicon wafer.

Figure 5: Screen printer for edge isolation

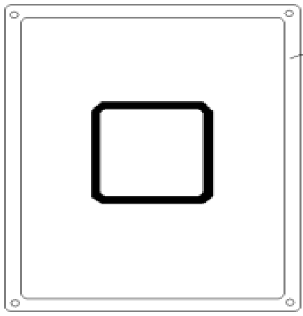

Figure 6: Designed screen used for edge isolation

C. $POCl_3$ Diffusion

Solar cells following texturing and cleaning are subjected to phosphorous diffusion to form n-p junctions. After edge isolation, the wafers are kept on a tray made of glass for the diffusion process. The tray was cleaned with the Isopropyl Alcohol (IPA) solution before use. At first the diffusion machine is turned on and the centre zone temperature is set to 600 °C. Once the temperature reached 600°C the tray containing the wafers were transferred to the diffusion chamber. It is necessary to make sure that special care is taken while transferring so that the wafers don't break. After the wafers are kept inside the container mouth is closed properly and care also has to be taken to check whether the gas is properly going out through the exhaust system. Then nitrogen gas is turned on and we have to wait for 10 minutes and then increase the temperature to 875 °C keeping the nitrogen gas on. After 875 °C is reached nitrogen gas is turned off and oxygen and $POCl_3$ (Phosphorus oxychloride) were turned on simultaneously. Then we have to wait for 10 minutes in this condition and after 10 minutes of diffusion time oxygen and $POCl_3$ gas are turned off simultaneously and nitrogen gas is turned on and we have to allow the nitrogen gas to flow for 10 minutes. After 10 minutes nitrogen gas is turned off and only oxygen gas is turned on for the next 10 minutes. After that oxygen gas is turned off and nitrogen gas is allowed to flow for 10 minutes. Finally after 10 minutes the temperature of the chamber is reduced to 600 °C from 875 °C and during this stage nitrogen gas is kept turned on. Once the temperature of the chamber dropped to 600 °C, the nitrogen gas is turned off and the wafers are ready to take out. Special heat protective gloves should be used because all these things are done at very high temperature so safety has to be ensured. Once the wafers are cooled naturally, it is processed for the next stage. Figure 7 shows the phosphorous doped silicon wafer.

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

D. Back and front surface metallization (Screen Printing)

Screen printing process is most commonly used to form metal contacts on back and front surfaces of solar cells. Following diffusion, screen printed metallic contacts are formed to form electrical contacts to n and p doped regions. A thick, viscous metal solution or paste is forced through stainless screen grid onto the wafer in selected lithographically defined open regions in the screen. The metal lines on the front surface (n-type) are made of silver and on the back surface (p-type) are made of aluminum. Aluminum contact on the wafer backside also serves to form a heavily diffused p++ layer that reduces contact resistance and enhances back surface reflectance. Appropriately-designed screens are used for this process, and screen printers are used to form Ag and Al contacts to front and back solar cell surfaces. The printing process begins as a silicon wafer is placed onto the printing table. A very fine-mesh print screen mount within a frame, is placed over the wader; the screen blocks off certain areas and leaves other areas open, where the paste can go through. The distance between wafer and screen is carefully controlled (called the 'snap-off' distance). Screens used for front side printing typically have a much finer mesh size than do backside screens, due to the finer metal lines required on the front side. After a measured amount of paste is dispensed onto the screen, a squeegee distributes the paste over the screen to uniformly fill the screen openings. As the squeegee moves across the screen, it pushes the paste through the screen openings and onto the wafer surface. Back side screen printing done by using aluminum paste. This process must be tightly controlled for temperature, pressure, speed, and many other variables. After each printing step the wafer goes to a drying furnace to solidify the paste. The wafer is then transferred to another printer for printing additional lines on either the front or back side of the wafer. Each solar cell has conductive lines on both front and back sides that are printed using screen masks and which have different functions. The complete screen printed solar cell is shown in Figure 8. The silver lines on front side are much more narrow and delicate than those on the backside; some manufacturers perform the backside print steps first, and then flip the wafers over to print front side contact, minimizing the potential for damage during handling.

Figure 8: Complete screen printed solar cell

E. Drying

After screen printing, the silicon wafers are required to go through drying at relatively low temperature (around 120°C) for certain period. In our experiment, we placed the wafers after each time edge isolation, back and front side printing in a preheated oven at 120°C for 10 minutes so that the paste gets attached well to the wafer surface.

F. Rapid Thermal Annealing (RTA)

Following screen printing, high temperature process is used to cure contacts in order to form ohmic contacts. The rapid thermal annealing furnace is used to cure or fire screen printed contacts on silicon solar cells. In order to establish an ohmic contact (low resistive contacts), contact firing is recommended in silicon solar cell processing. Conventionally, any RTA process is capable to do the process. In this case, a belt conveyer system integrated RTA processing unit is used for a continuous processing of contact firing. A conveyor belt furnace capable of reaching 1000 °C temperature is used for this step. In our experiment, RTA of screen printed cells is done at a temperature of 500, 600 and 800 °C respectively. The wafers are passed through a moving belt which goes inside the RTA machine. Rapid Thermal Annealing is important because it provides proper contact between the conductor and the semiconductor. Figure 9 shows the contact firing process of screen printed Si solar cell.

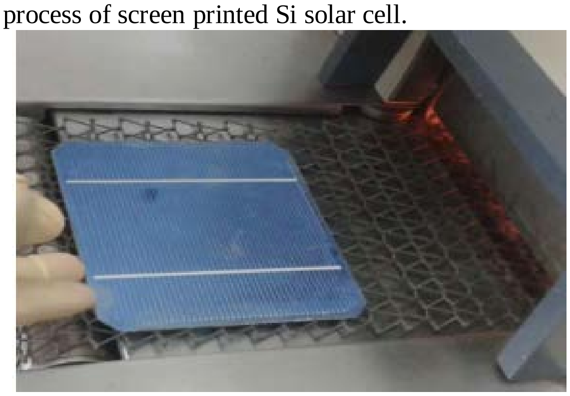

Figure 9: Contact firing at RTC furnace

G. Light Current Voltage (liv) Testing

After finishing a complete solar cell, LIV (Light-Current-Voltage) testing is done to evaluate the performance of the cell and mainly to calculate the efficiency of the solar cell. Initially the wafer is kept on the gold plated tray and then the bus bar of the cell is aligned with the pogo pins. Then the vacuum is turned on. Then the power supply and the control box is connected to the Laptop. LIV measurements using inexpensive, flash, xenon light source for illumination. LIV data acquisition is based on a custom-designed electronic interface integrated with high resolution, programmable voltage supply. Voltage across the solar cell is applied to measure the light generated photo-current. A user-friendly LabVIEW interface capable of writing data in ASCII format forms the basis of data acquisition. Spectral distribution of xenon high intensity plasma discharge lamp is light is closest to the solar spectra, and is industry standard. The flash LIV system is capable of measuring small (~ 10 cm^2) and large (up to ~15x15 cm^2) solar cells. The intensity variation is controllable in ~ 10 mW/ cm^2 to 100 mW/ cm^2 through simple absorptive metallic filters. Figure 10 shows the LIV measurement system.

Figure 10: LIV measurement system

IV. RESULTS AND DISCUSSION

Solar cells are characterized by their ability to convert sunlight into electricity. The light intensity (L)-current (I)-voltage (V) test is a series of measurements performed on complete solar cells to measure their operating characteristics. The LIV test identifies characteristics such as short circuit current (Isc), open circuit voltage (Voc), fill factor (FF) and power maximum (Pmax). These results can be used to determine the efficiency of solar cell. Solar cells are tested under one-sun conditions using Xenon-arc lamps; a xenon spectrum is closest to sunlight. Data acquisition based on programmable current-voltage source power supplies capable of handling current up to ~ 8 A 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 Figure 11.

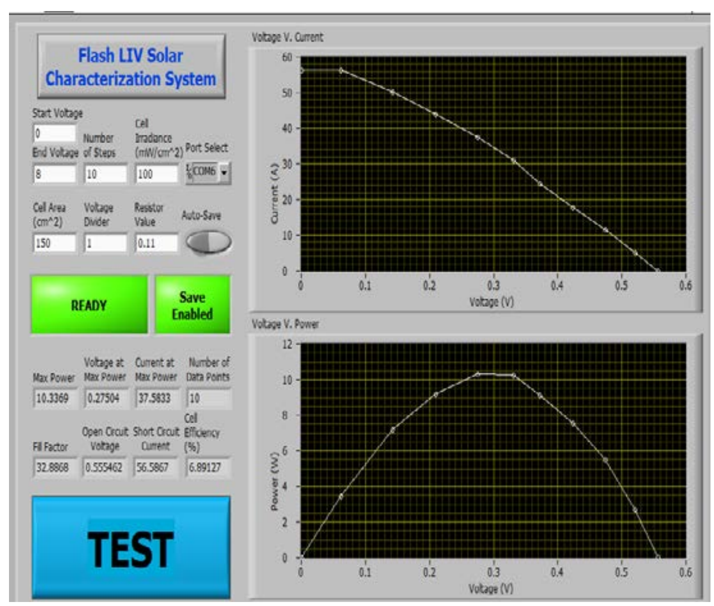

Figure 11: Measured LIV data

It gives the V-I curve of our fabricated solar cell. From LIV data, we have found the following results of our fabricated monocrystalline silicon solar cell which are, Maximum power is 10.3369W, Voltage at maximum power is 0.27504V, Current at maximum power is 37.5833mA, Open circuit voltage is 0.555462V, Short circuit current is 56.5867mA, Fill factor is 32.8868 and Efficiency is 6.89%. The efficiency of our fabricated solar cell is quite low because it is the first locally fabricated solar cell in Bangladesh. Optimization of processing techniques as well as the air quality, water quality and other chemicals are needed to increase the efficiency of solar cell.

V. CONCLUSION

For the first time, a laboratory has been set up by BAEC to fabricate the monocrystalline silicon solar cell locally. We have fabricated our solar cell in this Laboratory. The efficiency of our fabricated solar cell is about 7% which is quite low as compared to the commercially available solar cell in the market. Our main objective was study of solar cell fabrication technology and fabrication of a monocrystalline silicon solar cell locally. There are lots of challenges to increase the solar cell efficiency. 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 7%. 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, 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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