International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 10 Issue 11 Series II || November 2021 || PP 01-07

Characterization of Monocrystalline Silicon Solar Cells based on the Phosphorus Diffusion Temperature

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ABSTRACT*: Phosphorus diffusion process for forming P-N junction is the heart of the silicon solar cell fabrication. One of the most important parameters that controls the diffusion profile of phosphorus into the silicon wafer is the temperature. This study focused on the influence of diffusion temperature on the emitter sheet resistance, carrier concentration, junction depth and solar cell parameters. To evaluate the influence of the diffusion temperature in electrical characteristic of the solar cells, diffusion temperature varied from 775ºC to 850^{o}C at a constant time of 88 minutes. All the diffusion processes carried out under 1900/2800-SCCM POCl3/ O_2 flow rate for pre-deposition& 1200/2000 for drive in. The results show a significant decrease in sheet resistance with increasing diffusion temperature. The highest cell efficiency was 18.36% corresponding to the sheet resistance of 41.7Ω/□ at 800 ℃*

KEYWORDS - *silicon solar cell, POCl3 diffusion, sheet resistance, emitter, temperature, Doping Concentration, Junction depth*

Date of Submission: 04-11-2021 Date of Acceptance: 18-11-2021

I. INTRODUCTION

With increasing the demand of fossil fuel, many researchers are trying to find reliable, clean and equitable substitutes for finite energy resources. The use of excessive fossil fuels causes a serious of environmental problems that harms to human health and the constraints of social progress. The one of the most promising strategies aiming is photovoltaic technology to deal with this problem by harvesting sunlight and thus clean and affordable solar electricity obtained [1-2]. Crystalline silicon (c-Si) solar cells currently dominates roughly 90% of the PV market due to the high efficiency (η) of up to 25% [3]. The diffusion process is the heart of the silicon solar cell fabrication. The n-type emitter of most crystalline p-type silicon solar cells is formed by phosphorus diffusion [4]. The n-type dopant source comprises of phosphorus compounds along with N_2 and O_2 gaseous environment is widely used in the thermal diffusion for commercial solar cell fabrication process. Phosphorus compounds react with O_2 and create a glass layer on the silicon surface (pre-deposition) [5]. The element phosphorus then penetrates into the silicon wafer (drive-in). A common P diffusion method is to expose Si wafers in a furnace at high temperature to an atmosphere of POCl3 and O_2 (with N_2 as a carrier gas), forming a phosphor silicate glass (PSG) on the wafer surfaces [6-7]. The popularity of $POCl_3$ diffusion can be attributed to the low costs, good stability, relative simplicity, and high throughput of the available production equipment [8-9]. The $POCl_3$ diffusion process continues to be optimized to support higher efficiency solar cells. Diffusion process depends on several factors; temperature, time and gas environment. One of the most important parameters that controls the diffusion profile of phosphorus into the silicon matrix is the temperature [10].

In this study, we will vary the phosphorus diffusion temperature, study its effect on the physical parameter as sheet resistance, and then correlate this variation with the electrical parameters of the solar cell as open circuit voltage, short circuit current, fill factor and efficiency. Simulation of a monocrystalline silicon solar cell diffusion process done using TCAD software to investigate the effect of diffusion temperature on carrier concentration and junction depth.

II. EXPERIMENTAL DETAILS

In this work, we evaluate how the diffusion temperature influence the properties of emitter and solar cell characteristics.

2.1 Emitter Formation

In diffusion process, the main equipment of interest is a cylindrical diffusion tube furnace, shown in Fig. 1. In a quick description, the furnace contains along the circumference-wall several heating resistances separated in three zones. Each zone has an independent power source used to control the temperature of the batch. This is mainly because one of the most important parameters that controls the diffusion profile of phosphorus into the silicon matrix is the temperature.

The wafers are vertically placed into a quartz support for loading 156 × 156 mm2 square wafers. Every wafer is placed at a distance of about 3 mm next to each other. The support is placed into the quartz tube and is heated to high temperature. The diffusion process carried out in two stages, pre-deposition and drive-in. At the pre-deposition stage, POCl3 and O2 gases are used along with the nitrogen (N2) as a carrier gas. The presence of O2 during P-diffusion is very essential as POCl3 reacts with O2 at higher temperatures and forms PSG. When the PSG was deposited in the pre-deposition stage, the dopant profile leads to a shallow junction depth and a high surface concentration. In the drive-in stage, a deeper junction was formed as phosphorus atoms diffuse deeper, thus thicker emitter and a lower surface concentration of dopant was achieved. Table 1 illustrate diffusion process parameters at various temperatures.

The P-diffusion by using liquid $POCl_3$ as a precursor can be understood from the following equations [11-12]:

$POCl_3$ (liquid) + N_2 (bubble) → $POCl_3$ (vapor) (pre-deposition) **(1)**

$4POCl_3$ (g) +$3O_2$ (g) → $2P_2O_5$ (l) + 6Cl2 (g) **(2)**

$2P_2O_5$+5Si → SiO2+ 4P (drive-in) **(3)**

P + 3Si → n-type doped Si **(4)**

2.2 Solar cell Fabrication Processes

Monocrystalline silicon solar cell was fabricated based on the inline processes used on the joint Egyptian- Chines Renewable Energy Laboratory, Sohag, Egypt.

Boron doped, CZ Si wafers of size 156 × 156 mm^2 with thickness 180 µm and bulk resistivity in the range of 0.8-2 Ω cm were used as the starting material for the solar cell fabrication. Alkaline chemicals followed by alkaline texturization removed the saw damages and the residual contamination. Consecutively, P-diffusion was carried out by using $POCl_3$ in a tube furnace. The phosphor silicate glass formed during diffusion process was removed in buffered HF followed by edge isolation. Silicon nitride (Si_3N_4) ARC of thickness ~ 84.7 nm and refractive index ~2.0 was deposited in tube plasma enhanced chemical vapour deposition (PECVD) system. The front and back contacts were made by using conventional screen-printing technology and co-fired to realize the ohmic contacts as well as aluminum (Al) back surface field (BSF).

Fig. 1 Diffusion furnace

Table 1 Diffusion process parameters at various temperatures

Diffusion Process Parameters	
Flow of $POCl_3/O_2$ (pre-deposition)	1900/2800 SCCM
Flow of $POCl_3/O_2$ (Drive-in)	1200/2000 SCCM
Pre-deposition time	1000 sec [16.6 min.]

Drive in time	500 sec [8.3 min.]
pressure	1 atm
Diffusion temperature	
Pre-deposition	**Drive in**
775	825
800	850
825	875
850	900

2.3 Characterization Techniques

Sheet resistance measurement was performed by four-point probe method. Current-voltage (I-V), power-voltage (P-V) characteristics, and the parameters of the solar cells were determined using Solar Cell Tester (SCMT) with a pulsed xenon lamp.

III. RESULTS AND DISCUSSION

3.1 Emitter Sheet Resistance

Average values of the emitter sheet resistance as a function of $POCl_3$ diffusion temperature is shown in Table 2 and Fig.2 respectively. We observed that, sheet resistance reduced with temperature increase. Sheet resistance reduced from 73 Ω / □ at 775 ^oC to 16.5 Ω / □ at 850 ^oC

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Table 2 Variation of sheet resistance with diffusion temperature

Temp. (^oC)	R_{Sheet} (Ω / □)
775	73
800	41.7
825	27.15
850	16.5

Table 3 Simulation results for the variation of carrier concentration and junction depth with diffusion temperature

Diffusion temperature (℃)	Peak doping concentration (Cm^{-3})	Junction depth (μm)
775	3.932697E21	1.442308
800	4.44623E21	1.730769
825	4.921667E21	2.152955
850	5.007992E21	2.788462
1000	6.268370E21	9.546043

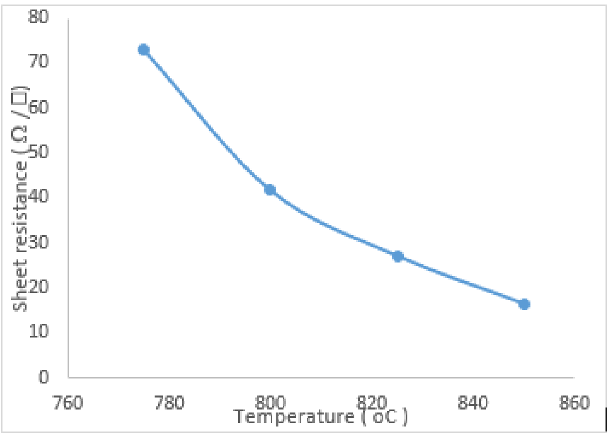

Fig. 2 Variation of emitter sheet resistance with diffusion temperature

As result of the lack of the necessary equipment's, to measure the physical changes that occur inside the cell as result of changing the temperature. We are trying to clarify the effect of changing diffusion temperature on carrier concentration and junction depth of diffused emitter through TCAD simulation program and this simulation is for illustration.

Table 3 and Fig. 3 show the variation of doping concentration and junction depth with temperature. Higher temperature resulted in a higher active surface doping concentration and a deeper junction. This behavior is explained by the variation of the coefficient diffusion and the limit of solubility of phosphorus with the temperature. In addition, we observe a reduction in the sheet resistance of the emitter when the temperature increases.

At 775°C, the surface concentration is 3.932697E21cm^{-3}. It increases up to 6.268370E21cm^{-3} at 1000 °C and the corresponding junction depths increase from about 1.44 to 9.54µm.

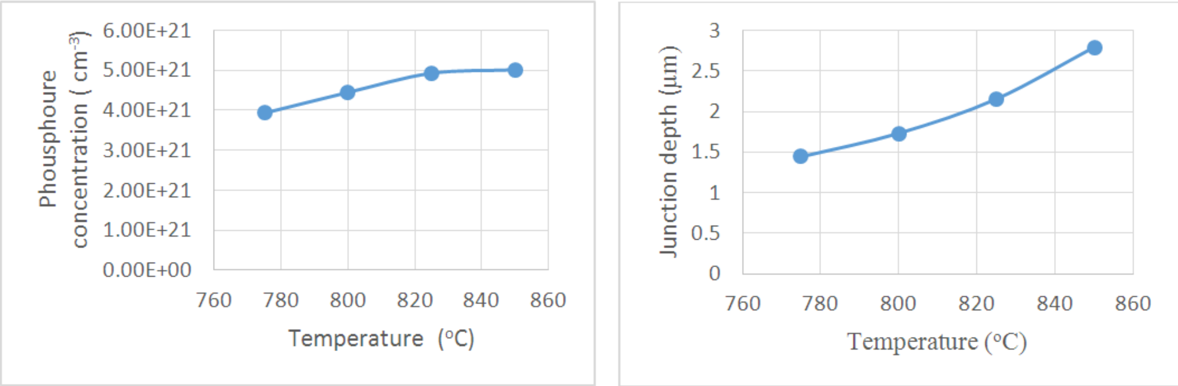

Fig. 3 Simulation results of the variation carrier concentration and junction depth with diffusion temperature

3.2 Solar Cell Characteristics

Average values of the electrical parameters of the solar cells as a function of $POCl_3$diffusion temperature are given in Table 4, Fig.4 and Fig. 5

Figure 4 show that, low temperature exhibits the highest series resistance of 6.711**Ω**, highest recombination current of 0.04733 A and lowest shunt resistance of 108.55**Ω**. This leads to lowest short circuit current density and open circuit voltage, this consequently leading to the lowest fill factor and lowest efficiency. Shunt resistance rises with increasing diffusion temperature and achieve the maximum value of 395.7 **Ω** at 825 ^{o}C, also series resistance and recombination current falls to 5.749 Ω and 0.01225 A respectively with increasing diffusion temperature to 800 ^{o}C.

The efficiency then drops off for further temperature increase. This is due to the much poorer fill factors, which can be attributed to decreasing shunt resistance and rising series resistance and recombination current at temperature above 800 ^{o}C as shown in Table 4.

Fill factor can be observed to rise with increasing doping concentration. Additionally, shunt resistance rises and series resistance falls with increasing junction depth due to the reduction in potential shunt paths and lower emitter sheet resistance. The thinnest emitter exhibits the highest series resistance, leading to the poor fill. Interestingly, the thickest emitter (850 °C) has the lowest short circuit current. This may be a result of the very high doping levels in the emitter layers (> 10^{20} cm^{-3}) leading to proportionally greater photocurrent losses for thicker emitters. The same drop can be observed in V_{OC} where the voltage decreases from an average value of 0. 631 V at 800 ^{o}C down to 0.626 V at 850 ^{o}C. These lower sheet resistances are favourable for improving the efficiency of a solar cell. Since higher diffusion, helps to increase doping concentration of phosphorus atoms.

Cell diffused at 800 °C temperature produced better performances as compared to the others; maximum power is 4.429 W, the maximum power voltage is 0.528 V, the maximum power current 8.23 A, open circuit voltage 0.632 V, short-circuit current 8.82 A, fill factor 79.307%, cell efficiency about 18.36%. Figure 6 show I-V and P-V curves of the best efficiency solar cell diffused at 800 ^{o}C.

Table 4 Parameters of silicon solar cells for different diffusion temperature

Temp. (^{o}C)	I_{SC}	V_{OC}	FF	R_S (Ω)	R_{Sh} (Ω)	Ir (A)	Eff.
775	8.4833	0.62711	76.87	6.711	108.55	0.04733	17.0266
800	8.80025	0.63166	79.307	5.749	344.167	0.01225	18.3608
825	8.418	0.6268	81.08	5.823	395.7	0.0149	17.552
850	8.1526	0.6266	80.51	5.967	364.4	0.0269	17.024

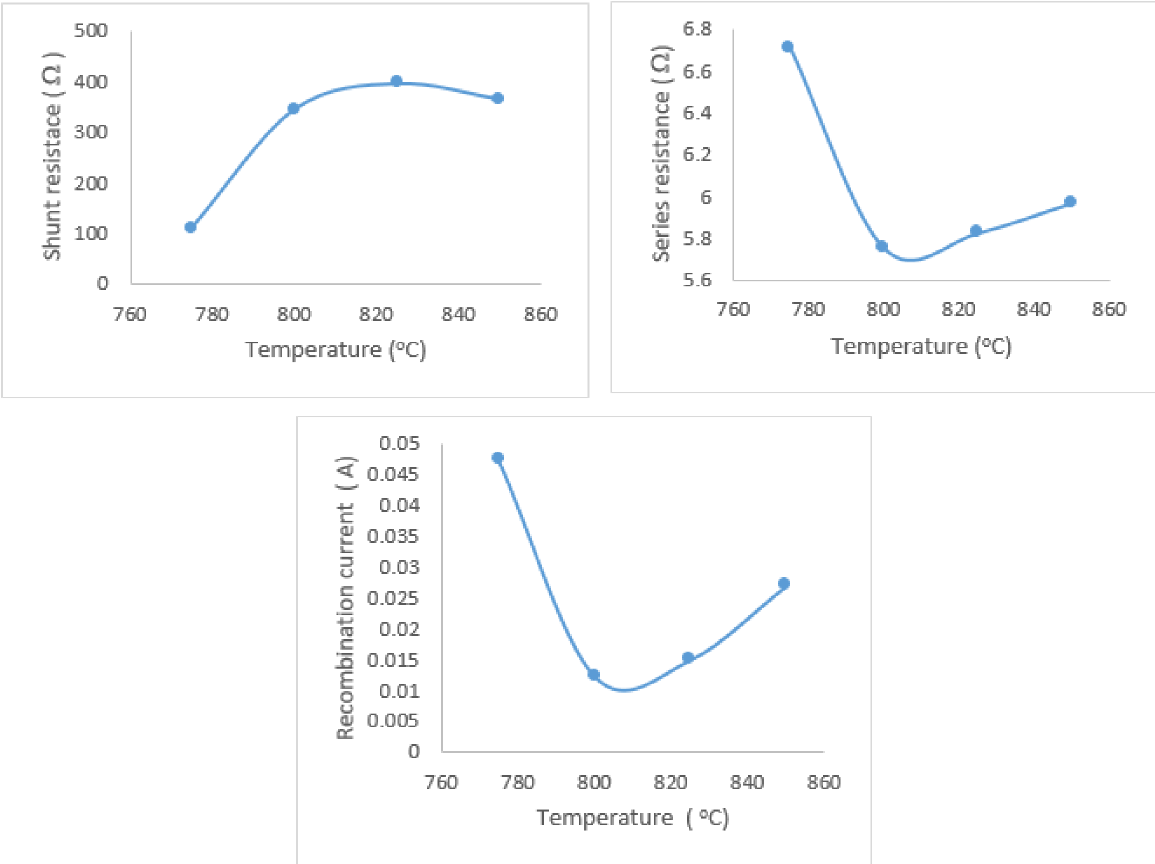

Fig. 4 Effect of diffusion temperature on solar cell shunt resistance, series resistance and recombination current

IV. CONCLUSION

The effect of Phosphorus diffusion temperature during monocrystalline silicon solar cell fabrication has been studied. When the temperature increased from 775 ºC to 850 ºC, the average sheet resistance of 73 Ω/□ reduced to 16.5 Ω/□. The series resistance reduced with the increase of the diffusion temperature. Samples diffused at 800 °C temperature produced better performances as compared to the others. The data shows that the maximum power is 4.429 W, the maximum power voltage is 0528 V, the maximum power current 8.23 A, open circuit voltage 0.632 V, short-circuit current 8.82 A, fill factor 79.307%, cell efficiency about 18.36%. The obtained results demonstrated that, the electrical properties of the fabricated mono-crystalline silicon solar cells are strongly dependent on the phosphorus diffusion temperature.

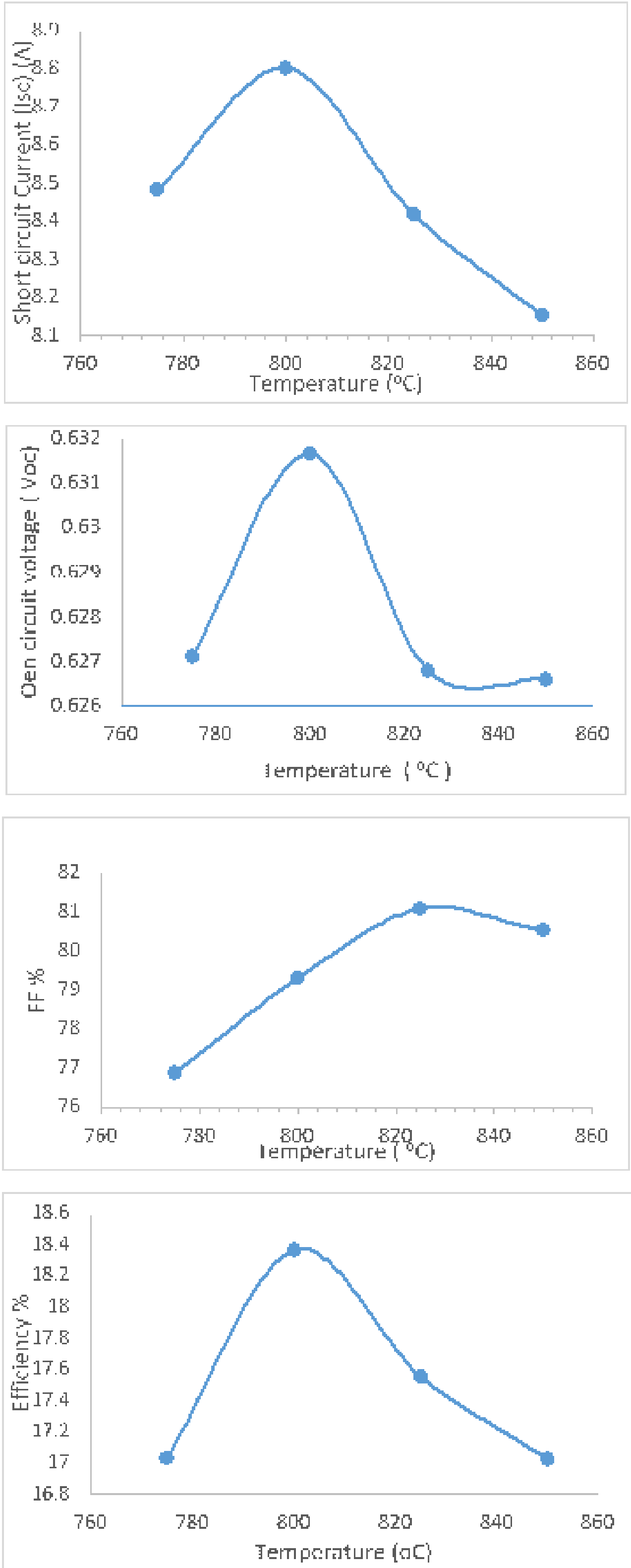

Fig. 5 Effect of diffusion temperature on; short circuit current, open circuit voltage, fill factor and efficiency of solar cell

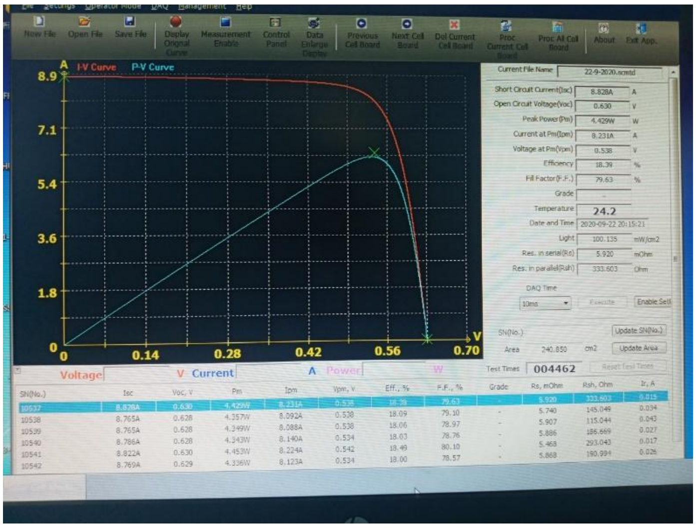

Fig. 6 Current–voltage and power–voltage characteristic of monocrystalline silicon solar cell for emitter diffused at 800 ^{o}C

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R.M. Ali, et. al, "Characterization of Monocrystalline Silicon Solar Cells based on the Phosphorus Diffusion Temperature.” *International Journal of Engineering Science Invention (IJESI)*, Vol. 10(11), 2021, PP 01-07. Journal DOI- 10.35629/6734