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Phosphorus profile optimization for conventional crystalline silicon solar cells emitters

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Abstract

The basic mechanisms of dopants diffusion in silicon are translated from Fick's laws. Their resolutions led us to determine the distribution of impurities versus time. This distribution is described mathematically by a Complementary Error Function in a first step and a Gaussian redistribution in a second time. The best approach is designed using a numerical analysis and simulation. To do this, we are interested in simulating the phosphorus diffusion by the Silvaco® Simulation Code. The first results obtained led us to initiate a reflection on the influence of diffusion parameters on the electrical characteristics of solar cells. Thus, various simulations were conducted to show the influence of temperature and diffusion time on the shape of diffusion profiles, and this while maintaining a surface concentration of phosphorus in constant close to the solubility limit of this dopant in silicon. Controlling the formation of emitters by the variation of the diffusion parameters is therefore an effective way to improve the quality of emitters and an opportunity to increase the performance of mc-Si conventional solar cells by about 2.5% absolute.

Keywords: Solar Cell, Crystalline Silicon, Diffusion, Emitter, Passivation
PACS:

1. Introduction

The emitters of the industrial silicon solar cells formed by $POCl_3$ diffusion is well known and largely used in the photovoltaic industry. During the diffusion, the phosphorus oxychloride ($POCl_3$) reacts with oxygen to form the Phosphorus Silicate Glass (P_2O_5) which is deposited on the silicon surface and releases the phosphorus which can then diffuse far in the silicon to form the p-n junction. This diffusion can be obtained in a conventional furnace under atmospheric pressure, but this technique present the difficulty to ensure the homogeneity of the formed emitter. However, another diffusion technique allows phosphorus doping under low pressure starting from a liquid source; the $POCl_3$. This allows an increase in the kinetic of gases which offer a better uniformity on the solar cells and a good reproducibility.

Several types of emitters can be obtained with the variation of the diffusion parameters, namely: temperature, time, pressure, surface concentration as well as, the addition of a possible pre-oxidation step. This latter is an enough method for the control of the presence of the electrically active phosphorus. In our study we are interested to the low sheet resistance emitter which is necessary for a good ohmic contact by screen-printed method. The numerical simulation code (Silvaco®) is used in order to show the effects of the phosphorus diffusion parameters on the performances of the crystalline silicon.

2. Modeling

To model the phosphorus diffusion profile in crystalline silicon, we have based on the PLS model included in Silvaco Athena® Code for an emitter with initial boron doping of 10^{16} cm-3 under a furnace pressure of 0.2 bars.

The diffusion of phosphorus in silicon is based on the Fick's laws, which stipulates that the diffusion profile follows initially a Complementary Error Function and a Gaussian function in a second stage. However, an experimental phosphorous diffusion profile was used to validate our numerical simulation results.

This experimental profile was obtained with phosphorus diffusion in crystalline silicon at 825°C during 30 minutes. The sheet resistance of emitter was about 40Ω/sq. The phosphorous profile was determinate by the Secondary Ion Mass Spectroscopy (SIMS).

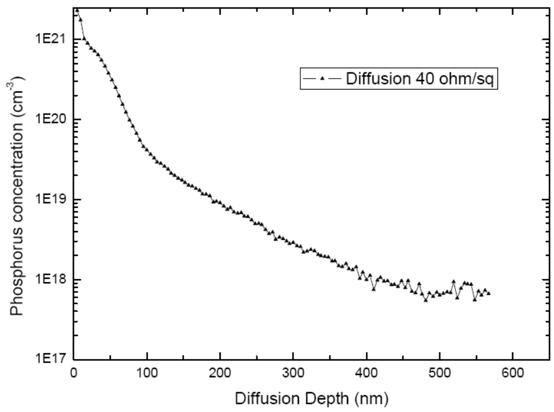

Figure 1 SIMS phosphorus diffusion profile.

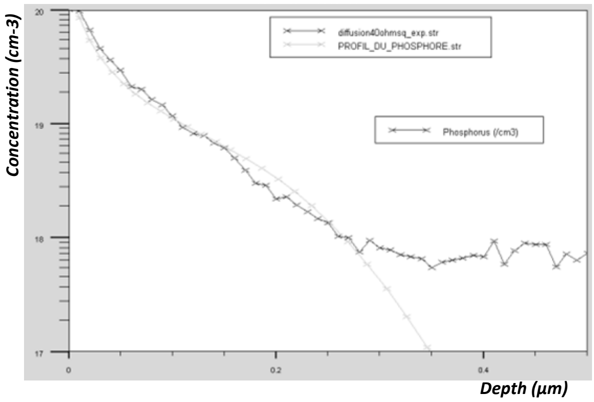

Figure 2 Experimental phosphorus diffusion profile modeling.

By using the Silvaco simulation code we can adjust the adequate profile to model the SIMS experimental profile (figure 2).

In other hand, we varied the diffusion parameters for a thorough study of the diffusion profiles:

2.1. Influence of temperature

The figure below show the variation of phosphorous profile with different diffusion temperature. As the temperature increases, doping increases, and the formed junctions are deeper. This behavior is explained by the variation of the coefficient diffusion and the limit of solubility with the temperature. In addition, we observe a reduction in the sheet resistance of the emitter when the temperature increases, as well as a lengthening of the formed junction. We present the following profiles for a 45 min diffusion times.

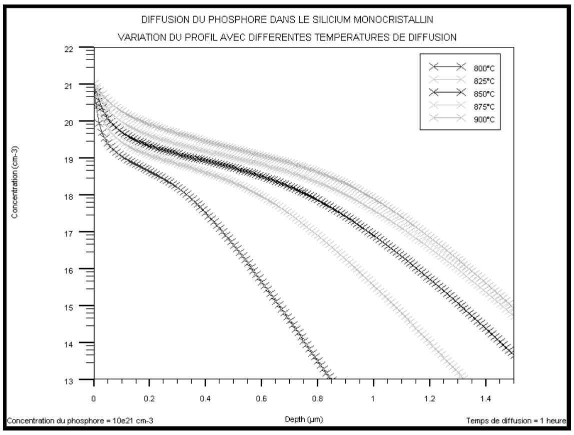

Figure 3 Variation of phosphorus diffusion profile versus temperature

The temperature is the key parameter for the phosphorus diffusion in silicon, a range of 800 to 850°C is allowed for acceptable sheet resistances in photovoltaic industry.

2.2. Influence of diffusion time

Solving Fick's equations, leads us to two cases for doping distribution: pre-deposition and the drive-in steps. One could however, easily to note that the influence of the diffusion time is more important for a fixed pre-deposition time and a variable drive-in time, since the quantity of phosphorus deposited at the pre-deposition time is the infinite source of the doping agents for the redistribution.

A longer drive-in time allows a lengthening of the concentration profile which brings amount of phosphorus introduced into silicon. The following figure illustrate an increase in the junction depth, and a decrease in the sheet resistance, at 800°C:

2.3. Influence of surface concentration

When the flow of $POCl_3$ is higher, doping increases consequently, since when the doping concentrations is lower, the quantity of phosphorus is insufficient to obtain uniform phosphorus glass. When the surface concentration increases, a strong non-linearity are observed on the profiles

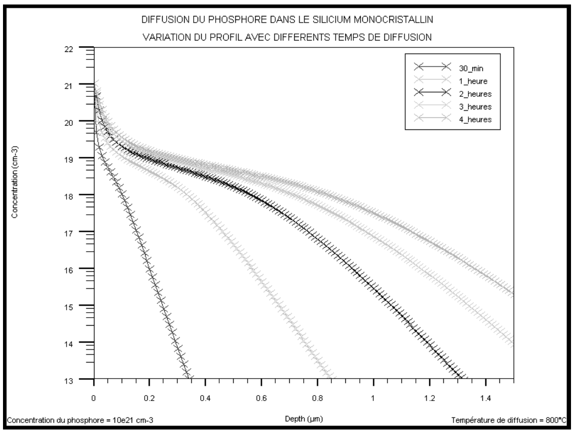

Figure 4 Variation of phosphorus diffusion profile versus diffusion time

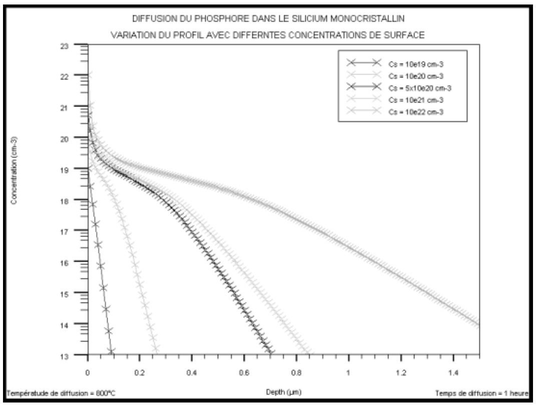

Figure 5 Variation of phosphorus diffusion profile versus phosphorus concentration

3. Results and discussion

3.1. Optimization of the emitter formation - evaluation of the dead layer

At high phosphorus concentrations, the emitter has an increased sensitivity to recombination. This is manifested by the creation of a zone called the "dead layer" which characterizes the presence electrically inactive phosphorus, due to the formation of precipitates.

The optimization of the emitter formation leads to the minimization of the formed dead zone. This area can be evaluated directly from the diffusion profile of phosphorus (SIMS profile) and the intersection with solid solubility and the charges concentration.

3.2. Effect of the diffusion parameters on the electric characteristics of the solar cell

Several studies have shown the effect of doping on the sheet resistance of the emitter, which will influence the parameters of the solar cell in the industrial processes.

We varied the concentrations of phosphorus and we obtained the following values for the emitter's sheet resistances:

TABLE 1

Emitter sheet resistance versus phosphorus doping

Surface concentration (cm^{-3})	Sheet resistance (ohm/sq)
$5x10^{20}$	159.48
$6x10^{20}$	138.63
$7x10^{20}$	133.56
$8x10^{20}$	136.06
$9x10^{20}$	135.97
10^{21}	147.64

We studied the influence of the variation of the diffusion parameters of the emitter on the solar cells characteristics. In the following table, we combine our results:

TABLE 2

Variation of the solar cells characteristics with the diffusion parameters

Parameters	Conventional solar cell	Simulated solar cell	Units
Isc	4.9	6.5	A
Voc	0.6	0.6	V
Vmax	0.5	0.5	V
Imax	4.7	6.1	A
Pmax	2.7	3.3	W
FF	82.9	82.1	%
η	13.6	15.73	%

When the new distribution of phosphorus is taken into account, we note a change of each electric performance (short-circuit current I_{sc}, tension in open circuit V_{oc}, fill factor FF and efficiency η).

Indeed, control of phosphorus diffusion by the variation of the diffusion parameters proved to be effective means to improve the emitter quality, since a variation of about 2.5% absolute in solar cell efficiency was observed.

4. Conclusion

In the case of conventional solar cells a high doping concentration of emitter ensure a better metallization by screen printing, but the front surface passivation is limited and it cause more losses by Auger recombination. Beyond these recombination, the characteristic of the profile obtained with a high phosphorus concentration, is that when the surface concentration exceeds the limit solubility, the atoms of phosphorus in excess are incorporated in the form of precipitates. In this zone, the life time is significantly reduced, so the area containing the precipitates is often called dead layer, this translates into a low spectral response of the solar cells.

The collection of charges is reduced and the saturation current of the emitter is achieved by these recombination. These two factors, influence respectively on the short circuit current and open circuit voltage. The reduction in the emitter doping thus seems a solution to limit the losses by recombination. However, a weak doping involves an increase in the resistive losses. The doping of the emitter has opposite effects on the characteristic of the solar cell. His profile should be optimized to reduce the series resistance while minimizing recombination.

In this work we have presented an optimization of the diffusion process by an innovating technique at low pressure furnace in order to control the emitter formation of solar cells while ensuring a good passivation and a better electrical collection.

Our result proves that we can target certain electrical properties only by the manipulation and optimization of $POCl_3$ doping profile. It is shown that an efficiency increase of about 2% absolute can be obtained with these manipulations.

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