Influence of Diffusion Parameters on Electrical Characteristics of mc-Si Solar Cells with Aluminum and Phosphorus Diffusion Performed in the Same Thermal Step

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The diffusion of phosphorus and aluminum in a single-step thermal process may reduce the production cost of multicrystalline silicon (mc-Si) solar cells. The goal of this paper is to analyze the influence of phosphorus diffusion parameters on the electrical characteristics of p-type mc-Si solar cells processed with a single-step diffusion of phosphorus and aluminum. To avoid the wafer bowing during aluminum paste firing, the aluminum was deposited by e-beam and co-diffused in the same thermal step that the phosphorus diffusion. First, the aluminum diffusion was performed and, then, the POCl\textsubscript{3} was introduced into the quartz tube. The steps of the phosphorus diffusion were experimentally optimized. The best result was found with the temperature of 875 °C. The POCl\textsubscript{3} concentration of 0.15% and the optimized phosphorus diffusion parameters lead to the efficiency of 14.1%. The reduction of the oxygen flow during ramp temperature and aluminum diffusion improved the efficiency.

Keywords: mc-Si solar cells, phosphorus and aluminum co-diffusion, diffusion parameter optimization.

1. Introduction

The efficiency of the solar cells fabricated by the industry in p-type multicrystalline silicon (mc-Si) wafers is around 17.8\%\textsuperscript{1}. This efficiency is about 2 \% lower than that of solar cells manufactured in Czochralski silicon (Cz-Si) wafers\textsuperscript{2}. However, the improvement of the quality of the mc-Si wafers combined with the cost reduction and the optimization of the production process across the entire chain lead to the dominance in the solar cell market with a share of about 60\%\textsuperscript{1}. In the last decade, different processes for texturing mc-Si wafer were developed and the reflectance was reduced down to 2 \%\textsuperscript{3,4,5,6}. The surface passivation was also improved\textsuperscript{7}.

The main disadvantage of multicrystalline material is the regions with low minority carrier lifetime in the wafer. Structural defects, such as grain boundaries and dislocations may be the causes of underperforming regions in mc-Si\textsuperscript{8,9}. The grain boundaries with metallic impurities agglomeration are usually centers of high recombination of the minority charge carriers\textsuperscript{10}.

Phosphorus diffusion gettering may remove impurities from the bulk to diffused region and it may reduce the effect of metallic impurities at the grain boundaries, resulting in an increase in the minority carrier lifetime\textsuperscript{11,12}. In addition, the phosphorus gettering does not add an extra step to the solar cell production process\textsuperscript{9,13} and is a well-known method to relocate iron from the bulk to the emitter, where it is less harmful\textsuperscript{14}.

The phosphorus diffusion is the classic dopant-process to produce the junction in solar cells manufactured in p-type crystalline silicon wafers since the 1970s\textsuperscript{15}. The diffusion is performed in a high temperature quartz furnace with a gaseous environment containing the phosphorus atoms (POCl\textsubscript{3}), nitrogen and small amount of oxygen. A phosphorus silicate glass grows on the surface of the wafer and phosphorus diffusion occurs from this glass. The largest use of the phosphorus diffusion is related to low costs, good stability, high throughput production and the gettering, mainly in mc-Si wafers.

Bentzen et al.\textsuperscript{16} reported that after phosphorus diffusion, the regions which had already shown higher values of minority carrier lifetime present a growth of this parameter, and the regions with low lifetime present little increase or no answer to the phosphorus gettering. The non-homogeneous behavior of the gettering is related to the dislocation density in the different regions of the material. The improvement of the poor quality areas is very important to increase the minority carrier lifetime in mc-Si wafers. Nevertheless, the processing at high temperatures causes degradation in mc-Si wafers, due to dissolution of precipitated impurities or to the formation of crystallographic defects. The diffusion to perform the emitter at low temperatures (less than 875 °C) and long duration may increase the lifetime and reduce the Fe concentration dissolved in the material\textsuperscript{16}.

The co-diffusion of phosphorus and boron or phosphorus and aluminum has the advantage of simplifying the fabrication process, avoiding single thermal steps, and the n\textsuperscript{+} and p\textsuperscript{+} regions can be performed in the same thermal step. Different methods have been developed\textsuperscript{17} for the co-diffusion of phosphorus and boron with different sources of dopants. For instance, a bifacial solar cell with passivated...
emitter rear totally diffused (PERT) was produced with co-diffusion of boron and phosphorus. The p' and n' layer were performed by atmospheric pressure chemical vapour deposition (APCVD) of boron (BSG) and phosphorous (PSG) silicate glass and co-diffusion in a quartz furnace. A SiN$_x$ antireflective coating was deposited on both faces and the BSG/SiN$_x$ stack was locally opened by laser radiation. The metallization was carried out by the screen printing technique. Solar cells manufactured in p-type Cz-Si wafers achieved the efficiency of 20.5%. Meier et al. reported the same efficiency for PERT solar cells with phosphorus diffusion using POCl$_3$ and boron glass silicate deposited by APCVD. Similar efficiency was obtained with PERT cells manufactured in n-type silicon wafers. In these cells, the co-diffusion was carried out with boron paste and phosphorus. The boron paste was deposited in both faces of one slave wafer and two wafers were put face-to-face with the slave in order to diffuse boron in one face of these two wafers and phosphorus in the other face during the co-diffusion.

However, few works were reported concerning the co-diffusion of phosphorus and aluminum. Moussaoui et al. develop a simple process to produce high efficiency multicrystalline solar cells, based on phosphorus pre-gettering and simultaneous diffusion of phosphorus and aluminum. The pre-gettering step was carried out to increase the minority carrier lifetime in the bulk. The efficiency reached was 16.1% with 4 cm$^2$ solar cell and metal grid performed by Ti/Pd/Ag evaporation. The co-diffusion of phosphorus and aluminum was also implemented to develop emitter wrap-through solar cells. The interdigitated p' and n' layers were formed by the evaporation of the aluminum finger grid followed by the co-diffusion of aluminum and phosphorus in a quartz tube. The contact grids were formed by Ti/Pd/Ag evaporation and shadowing masks. The efficiency achieved was 10.1% and 9.6% in solar cells processed in Cz-Si and mc-Si, respectively.

The phosphorus diffusion using POCl$_3$ continues to be optimized to improve the efficiency of solar cells. For instance, Li et al. reported the influence of phosphorus diffusion on the emitter formation of industrial solar cells. These devices are produced with a phosphorus diffusion in a thermal step and the aluminum back surface field (BSF) is formed by screen printing technique. The Al paste is fired in a thermal process using a belt furnace.

As an alternative to the industrial standard process to produce silicon solar cells, in this paper, a method is presented to perform the aluminum diffusion in the same thermal step of phosphorus diffusion, with aluminum deposited by electron beam physical vapor technique to avoid the wafer bowing. The Al paste deposited by screen printing to produce the back surface field may cause wafer bowing during the firing of metallization pastes, leading to wafer breakage. This way, to develop solar cells in p-type mc-Si wafers with co-diffusion of phosphorus and aluminum, steps of the process have to be experimentally optimized. For instance, POCl$_3$ concentration, diffusion temperature and time as well as gas flows affect the minority charge carrier lifetime and the sheet resistance of the emitter and, consequently, the performance of the mc-Si solar cells. In this scenario, the goal of this paper is to optimize the phosphorus diffusion parameters and analyze their influence on the electrical characteristics of mc-Si solar cells processed with a single-step diffusion of phosphorus and aluminum. Specifically, the POCl$_3$ concentration in the quartz tube furnace, the temperature and time of phosphorus diffusion and the oxygen and nitrogen flow rate were evaluated. Differently of the method reported by Moussaoui et al., the solar cells were developed without pre-gettering step and with the industrial screen printing metallization in the front face and in the rear face. The Al paste deposited by screen printing technique to produce the back surface field (BSF) may cause bowing in the wafers during the firing of metallization pastes, leading to the breaking of the wafers, then the aluminum was deposited by electron beam physical vapor method to perform the BSF and, in the same thermal step, the phosphorus emitter was produced.

2. Solar Cell Process and Methodology

A complete solar cell manufacturing process for n’pp’ multicrystalline silicon solar cells was developed by using p-type wafers, with resistivity of 0.5 to 2 $\Omega\cdot$cm. The phosphorus and aluminum diffusion was performed in the same thermal step. The developed process presents advantages if compared to the industry standard and to the typical process based on aluminum evaporated by the e-beam method.

In the first case, the proposed alternative process avoids the solar cell bowing because the aluminum was evaporated by e-beam and a metal grid with aluminum/silver paste was performed by screen-printing. In the industry standard process the Al paste is screen printed on whole rear area and, in a second step, the Ag/Al busbars are also screen printed. Then, the number of steps to manufacture the solar cells with the proposed process is similar to the industry standard, but the solar cell bowing is avoided due to the formation of the Al/Ag paste screen-printed metal grid on the rear aluminum BSF. Consequently, the wafer breakage can be reduced during the soldering.

In the second case, the silicon oxide growth is required to form the BSF in the manufacture of solar cells by diffusion of Al deposited by evaporation. Photoresist is deposited on one surface and silicon oxide is etched on the other surface. Thus, phosphorus diffusion occurs only on the front face of the mc-Si wafer. After the oxide etching in chemical solution, the aluminum on the back surface is evaporated and diffused. In the proposed process, the deposition of photoresist and oxidation steps were not necessary and,
then, the processing cost may be reduced. At the same time,
an oxidation process at high temperature, that may degrade
the mc-Si wafer, was not performed.

The developed process incorporated the following steps,
as Figure 1 shows: surface texturing with acidic solution, RCA
cleaning, aluminum evaporation, single step phosphorus and
aluminum diffusion in the quartz tube furnace, phosphorus
silicate glass removal, RCA cleaning, TiO₂ anti-reflective
coating (ARC) deposition, screen printing of the metal grid
in both faces, firing of metal pastes and laser edge isolation.

After the texturing process and RCA cleaning, an aluminum
layer of 2 µm thickness was evaporated by e-beam method.
Then, the aluminum was firstly diffused and, in the same
thermal step, the phosphorus diffusion was performed. In
order to optimize experimentally the phosphorus diffusion in
the quartz tube furnace, the influence of several parameters
of the process was analyzed, such as: POCl₃ concentration
(in volume) in the quartz tube, time and temperature of
phosphorus diffusion and gas flow during the diffusions.
After the diffusion of the dopants, the phosphorus silicate
glass was etched and a RCA cleaning was performed to
prepare the wafers to receive the TiO₂ anti-reflective coating
of 70 nm. Then, the Ag/Al metal grid was screen printed
on the rear face and the Ag grid was deposited on the front
face. Both pastes were fired in the belt furnace set at 870 ºC.

The electrical characteristics of the developed solar
cells were measured under standard conditions (100 mW/
cm², AM1.5G and 25 ºC) in a solar simulator calibrated
with a solar cell previously measured at CalLab - FhG-ISE
(Fraunhofer-Institut für Solare Energiesysteme), Germany.
The two-dimensional minority carrier diffusion length was
measured using the WT-2000PV device of Semilab, by LBIC
(light beam induced current) technique.

### 3. Results and Analysis

#### 3.1 POCl₃ concentration

To start the process development, the temperature of
aluminum diffusion was set equal to the phosphorus diffusion,
of 875 ºC. The aluminum was diffused during 90 minutes,
and phosphorus was diffused during 30 minutes, because
simulation by one-dimensional program PC1D and an in
house software to optimize the metal grid indicated that
for solar cells with back surface field (BSF), the n⁺ emitter
sheet resistance can range from 53 to 107 Ω/□. The POCl₃
concentration (CPOCl₃) was ranged and batches of solar cells
were manufactured. The results are shown in the Table 1.

The higher average efficiency was found for CPOCl₃ of
0.15%. The worst result was found for CPOCl₃ of 0.12%, due
to high sheet resistance that causes a high contact resistance
and, consequently, a low fill factor. The standard deviation
of sheet resistance decreases with the increase of POCl₃
concentration, indicating that the uniformity of the emitter
increases. For CPOCl₃ ≥ 0.15 %, the Jsc and Voc decrease
because the minority charge carrier recombination increases
in the emitter.

The Fig. 2 compares the electric current density as a
function of the applied voltage (J-V curve) for the solar cell
with the highest efficiency processed with the CPOCl₃ values
presented in Table 1. The lower series resistance occurs in
the solar cells processed with CPOCl₃ = 0.15 %, resulting in
the fill factor of 0.79, and in the efficiency of 14.1 %, as
summarized in Table 2.

#### 3.2 Phosphorus diffusion temperature

To evaluate the influence of the diffusion temperature in
electrical characteristic of the solar cells, this parameter was

![Figure 1. Sequence of the fabrication process of n⁺pp⁺ silicon solar cells in mc-Si wafers with phosphorus and aluminum diffusion in
the same thermal step.](image)

### Table 1. Average values of the sheet resistance (Rₛ), short-circuit current density (Jsc), open circuit voltage (Voc), fill factor (FF) and
efficiency (η) of the solar cells as a function of POCl₃ concentration.

<table>
<thead>
<tr>
<th>CPOCl₃(%)</th>
<th>Rₛ(Ω/□)</th>
<th>Number of cells</th>
<th>Jsc(mA/cm²)</th>
<th>Voc(mV)</th>
<th>FF</th>
<th>η(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>145 ± 50</td>
<td>7</td>
<td>28.7 ± 1.8</td>
<td>560 ± 8</td>
<td>0.47 ± 0.07</td>
<td>7.6 ± 1.5</td>
</tr>
<tr>
<td>0.15</td>
<td>64 ± 10</td>
<td>6</td>
<td>30.1 ± 0.2</td>
<td>588 ± 5</td>
<td>0.77 ± 0.01</td>
<td>13.7 ± 0.3</td>
</tr>
<tr>
<td>0.17</td>
<td>59 ± 5</td>
<td>6</td>
<td>28.7 ± 0.4</td>
<td>577 ± 2</td>
<td>0.71 ± 0.03</td>
<td>11.7 ± 0.4</td>
</tr>
<tr>
<td>0.20</td>
<td>59 ± 1</td>
<td>6</td>
<td>28.6 ± 0.7</td>
<td>532 ± 14</td>
<td>0.65 ± 0.03</td>
<td>10.0 ± 0.8</td>
</tr>
<tr>
<td>0.22</td>
<td>57 ± 1</td>
<td>6</td>
<td>28.4 ± 0.5</td>
<td>525 ± 8</td>
<td>0.63 ± 0.05</td>
<td>9.5 ± 0.9</td>
</tr>
</tbody>
</table>
Figure 2. Electric current density as a function of the applied voltage of the solar cells with the highest efficiency, processed with POCl$_3$ concentration of 0.12%, 0.15%, 0.17%, 0.20% and 0.22% and aluminum and phosphorus diffusion performed in the same thermal step.

Table 2. Short-circuit current density, open circuit voltage, fill factor and efficiency of the solar cells with the highest efficiency as a function of POCl$_3$ concentration.

<table>
<thead>
<tr>
<th>C$_{POCl3}$ (%)</th>
<th>J$_{SC}$ (mA/cm$^2$)</th>
<th>V$_{OC}$ (mV)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>30.9</td>
<td>573</td>
<td>0.59</td>
<td>10.2</td>
</tr>
<tr>
<td>0.15</td>
<td>30.2</td>
<td>592</td>
<td>0.79</td>
<td>14.1</td>
</tr>
<tr>
<td>0.17</td>
<td>28.7</td>
<td>578</td>
<td>0.73</td>
<td>12.2</td>
</tr>
<tr>
<td>0.20</td>
<td>29.6</td>
<td>550</td>
<td>0.67</td>
<td>11.0</td>
</tr>
<tr>
<td>0.22</td>
<td>28.8</td>
<td>534</td>
<td>0.67</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Modified for POCl$_3$ concentration of 0.15%. The average electrical parameters are presented in the Table 3. When the temperature was decreased from 875 °C to 850 °C, the average sheet resistance of (42 ± 3) Ω/□ increased to (168 ± 24) Ω/□ and all the electrical characteristics decreased. The series resistance increased with the reduction of the diffusion temperature ($T_p$), as Figure 3 shows, due to the increasing of the contact resistance. Therefore, in the next processes $T_p$ was set of 875 °C.

3.3 Phosphorus diffusion time

Another parameter that affects the performance of solar cells is the phosphorus diffusion time ($t_p$), because during phosphorus diffusion, the aluminum diffusion also occurs. This parameter was ranged for the POCl$_3$ concentration of 0.15 % and diffusion temperature of 875 °C. The phosphorus diffusion time of 70 minutes resulted in the sheet resistance of (42 ± 3) Ω/□. Comparing the results presented in Table 4, we observed an improvement of open circuit voltage and fill factor when $t_p$ was increased from 30 minutes to 70 minutes. Fill factor increased because the sheet resistance decreased. Figure 4 shows an enhancement of V$_{OC}$ with the increasing of the diffusion time, that was related to the deeper BSF because the aluminum diffusion occurred also during the phosphorus diffusion. The current density decreased due to the deeper pn junction and the augment of the minority carrier recombination in the emitter.

3.4 Gas flow influence

The oxygen flow during the entrance of the wafers in the quartz tube and the nitrogen flow during the Al diffusion may affect the solar cell efficiency. Table 5 presents the average electrical characteristics of the solar cells processed with different oxygen and nitrogen flows. The time of phosphorus diffusion was 70 minutes. The oxygen and nitrogen flow in the process A was 0.29 l/min and 4.68 l/min, respectively, and this process was considered as a reference. The oxygen flow was increased 50% in process B during the entrance of the wafers in the quartz tube. In the process C, nitrogen flow was decreased by 43% during the temperature ramp and Al diffusion. In the processes A, B and C the C$_{POCl3}$ was 0.15 % and in process D the C$_{POCl3}$ was 0.17 %. The oxygen flow was decreased by 65% during the entrance of the wafers and the nitrogen flow was reduced in 34% during the aluminum diffusion in process D. Table 5 shows that the electrical characteristics of solar cells of the process B and C were

Table 3. Average values of the sheet resistance and electrical parameters of the solar cells as a function of phosphorus diffusion temperature.

<table>
<thead>
<tr>
<th>$T_p$ (°C)</th>
<th>$R_s$ (Ω/□)</th>
<th>Number of cells</th>
<th>J$_{SC}$ (mA/cm$^2$)</th>
<th>V$_{OC}$ (mV)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>875</td>
<td>64 ± 10</td>
<td>6</td>
<td>30.1 ± 0.2</td>
<td>588 ± 5</td>
<td>0.77 ± 0.01</td>
<td>13.7 ± 0.3</td>
</tr>
<tr>
<td>850</td>
<td>168 ± 24</td>
<td>10</td>
<td>22.6 ± 4.9</td>
<td>465 ± 15</td>
<td>0.34 ± 0.07</td>
<td>3.7 ± 1.7</td>
</tr>
</tbody>
</table>
Table 4. Average electrical parameters of the solar cells as a function of the phosphorus diffusion time (t_P) with POCl_3 concentration of 0.15 %.

<table>
<thead>
<tr>
<th>t_P(min)</th>
<th>R_□(Ω/□)</th>
<th>Cells number</th>
<th>J_sc(mA/cm²)</th>
<th>V_oc(mV)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>81 ± 15</td>
<td>7</td>
<td>30.5 ± 0.4</td>
<td>573 ± 3</td>
<td>0.65 ± 0.02</td>
<td>11.4 ± 0.4</td>
</tr>
<tr>
<td>70</td>
<td>42 ± 3</td>
<td>4</td>
<td>29.5 ± 0.3</td>
<td>580 ± 4</td>
<td>0.71 ± 0.03</td>
<td>12.2 ± 0.6</td>
</tr>
</tbody>
</table>

Figure 4. Electrical characteristics at standard conditions of solar cells with the highest efficiency, processed with POCl_3 in the quartz tube during 30 and 70 minutes at the temperature of 875 ºC.

Table 5. Electrical characteristics of solar cells as function of oxygen and nitrogen flow variation (DGAS) during the entrance of the wafers in the quartz tube and Al diffusion, respectively, for aluminum and phosphorus diffusion temperature of 875 °C. The aluminum and phosphorus diffusion time was 90 and 70 minutes, respectively.

<table>
<thead>
<tr>
<th>Process</th>
<th>D_GAS (%)</th>
<th>C_POCl3 (%)</th>
<th>Cells number</th>
<th>J_sc(mA/cm²)</th>
<th>V_oc(mV)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0% O_2, 0% N_2</td>
<td></td>
<td>4</td>
<td>29.5 ± 0.3</td>
<td>580 ± 4</td>
<td>0.71 ± 0.03</td>
<td>12.2 ± 0.6</td>
</tr>
<tr>
<td>B</td>
<td>50% O_2, 0% N_2</td>
<td>0.15</td>
<td>5</td>
<td>27.4 ± 0.5</td>
<td>570 ± 8</td>
<td>0.68 ± 0.04</td>
<td>10.7 ± 0.8</td>
</tr>
<tr>
<td>C</td>
<td>0% O_2, 43% N_2</td>
<td>4</td>
<td>27.2 ± 0.7</td>
<td>534 ± 9</td>
<td>0.69 ± 0.02</td>
<td>10.0 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>65% O_2, 34% N_2</td>
<td>0.17</td>
<td>6</td>
<td>28.2 ± 0.4</td>
<td>577 ± 6</td>
<td>0.70 ± 0.05</td>
<td>11.4 ± 1.0</td>
</tr>
</tbody>
</table>

3.5 Minority charge carrier diffusion length

The two-dimensional distribution of the minority carrier diffusion length (L_D) measured in the solar cell with higher efficiency is shown in Fig. 7.

The average value of L_D was 132 µm and the standard deviation was around 24 %. Lower values of L_D were observed in regions of grain boundaries and under metal grid. The highest value of minority carrier diffusion length is of...
approximately 160 µm and it does not reach the thickness of the cell, which is around 240 µm.

4. Conclusions

After the experimental optimization of the process to manufacture solar cells with phosphorus and aluminum diffusion performed in the same thermal step, we concluded that the diffusion temperature of 875 ºC during 90 minutes and 30 minutes for aluminum and phosphorus, respectively, and the C_{POCl_3} of 0.15 % resulted in the highest efficiency. The phosphorus and aluminum diffusion performed in the same thermal step produced the sheet resistance in the phosphorus emitter of (64 ± 10) Ω/□. The efficiency achieved was of 14.1 %.

The analysis of the oxygen and nitrogen flow, during the steps of the entrance of the wafers in the quartz tube and aluminum diffusion, indicated that the reduction of the ratio of oxygen and nitrogen flow decreased the thickness of the aluminum oxide formed on the rear face, which increased the contact resistance between aluminum BSF and Al/Ag metal grid.

Table 6. Electrical parameters of solar cells as function of oxygen and nitrogen flow variation (D_{GAS}) during the entrance of the wafers in the quartz tube and Al diffusion, respectively, for aluminum and phosphorus diffusion temperature of 875 ºC. The aluminum and phosphorus diffusion time was 90 and 30 minutes, respectively.

<table>
<thead>
<tr>
<th>Proc.</th>
<th>D_{GAS} (%)</th>
<th>C_{POCl_3} (%)</th>
<th>Cells</th>
<th>J_sc (mA/cm^2)</th>
<th>V_oc (mV)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>0% O_2, 0% N_2</td>
<td>0.15</td>
<td>6</td>
<td>30.1 ± 0.2</td>
<td>588 ± 5</td>
<td>0.78 ± 0.01</td>
<td>13.7 ± 0.3</td>
</tr>
<tr>
<td>F</td>
<td>25% O_2, -15% N_2 (Al)</td>
<td>6</td>
<td>30.8 ± 0.4</td>
<td>576 ± 4</td>
<td>0.60 ± 0.05</td>
<td>10.7 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>25% O_2, -15% N_2 (Al)</td>
<td>0.17</td>
<td>4</td>
<td>30.2 ± 0.6</td>
<td>580 ± 3</td>
<td>0.68 ± 0.02</td>
<td>11.9 ± 0.5</td>
</tr>
</tbody>
</table>

Figure 5. J-V curve of the solar cells with the highest efficiency, processed with different gas flow and POCI3 concentration.

Figure 6. Electrical characteristics at standard conditions of solar cells with the highest efficiency, manufactured with process E, F and G.
5. Acknowledgements

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6. References


