HIGH EFFICIENCY P-I-N SOLAR CELLS WITH <I> LAYER DEPOSITED BY HOT-WIRE TECHNIQUE

Institute of Microtechnology, University of Neuchâtel, A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland

ABSTRACT

More stable amorphous silicon (a-Si:H) material obtained with the Hot-Wire technique requires high substrate temperatures (T_{sub} > 300°C) and low gas pressures (p_{dep} = 10^{-2} mbar). The second condition implies that heat transfer between the heater and the substrate is mainly dominated by thermal radiation; therefore, T_{sub} is strongly affected by the emissivity \( \varepsilon_{surf} \) of the growth surface. Here, it will be shown experimentally that \( \varepsilon_{surf} \) depends on the thickness of the growing a-Si:H layer; a significant variation in \( \varepsilon_{surf} \) during the deposition of the first 3000Å has been observed. With the help of a new heating concept, we integrated an intrinsic layer deposited at constant T_{sub} = 270°C into a p-i-n solar cells with initial efficiency of 8.7%.

EXPERIMENTAL

New heating system

Due to substantial thermal inertia, the conventional heater is not effective in compensating a fast change of the substrate temperature. To improve the response time...
of the substrate, we have integrated a low mass heater onto the substrate. The heating element is realised by a thin metallic film (chromium) deposited on the whole surface of one side of the substrate (see Fig. 2). As already described in detail [7], the substrate temperature $T_{\text{sub}}$ is controlled by the electrical power $P_{\text{el}}$ applied to the thin metallic film.

![Cross-section of the glass substrate and the metallic film acting as heating element. $Q_{\text{Cr}}$ represents the radiative losses emitted from the metallic surface, and $Q_{\text{surf}}$ those emitted from the surface of the substrate.](image)

**Films and cells preparation**

Device-quality a-Si:H films have been prepared in a UHV apparatus using the following deposition parameters: gas pressure of $10^{-2}$ mbar, hydrogen and silane flow rate of 10 sccm; the gas is decomposed by a tungsten filament with a length of 150 mm and a diameter of 0.3 mm diameter, heated at 1850 °C and placed at a distance of 5 cm from the substrate.

The solar cells, with an intrinsic layer of 4000 Å, were deposited on SnO$_2$-coated glass substrate (U2 from Asahi). The doped layers $p$ and $n$ were obtained within a separate PE-CVD reactor; this implied a transfer from one system to the other one by exposing each interface of the solar cell to the air. Finally, a sputtered ITO/Ag has been used for the back contact.

**RESULTS AND DISCUSSION**

**Surface emissivity $\varepsilon_{\text{surf}}$**

At low deposition pressure the substrate temperature $T_{\text{sub}}$ depends strongly on the surface emissivity $\varepsilon_{\text{surf}}$ in both heating systems. Therefore, it is necessary to determine how $\varepsilon_{\text{surf}}$ is influenced by the deposited a-Si:H film, this being important where the initial value of $\varepsilon_{\text{surf}}$ differs from the value for a-Si:H ($\varepsilon_{\text{a-Si:H}} = 0.6$). We have analysed two typical cases (see Fig. 3.): the deposition of a-Si:H on glass ($\varepsilon_{\text{glass}} = 0.9$) and on TCO ($\varepsilon_{\text{TCO}} = 0.3$). The determination of $\varepsilon_{\text{surf}}$ is evaluated from $T_{\text{sub}}$, measured with a Pt100 pasted on the surface of the substrate, and using the relation derived from the Stefan-Boltzmann law [8]:

$$\varepsilon_{\text{surf}} = \frac{P_{\text{el}}}{\sigma T_{\text{sub}}^4}$$

where $P_{\text{el}}$ is the electrical power density applied to heat the substrate, $A_{\text{Teac}}$ the thermal power contribution of the internal wall of the reactor determined experimentally and $\sigma$ the Stefan-Boltzmann constant.

![Measured effect of the a-Si:H thickness on the surface emissivity $\varepsilon_{\text{surf}}$ for the cases of a-Si:H deposited on glass substrate (Corning 7059) and on TCO substrate (SnO$_2$ textured). The dashed lines are the interpolated functions used for the simulations presented in the next section.](image)

In both cases, we observed, first, that the surface emissivity depends on the thickness of the deposited a-Si:H ($d_{\text{a-Si:H}}$ in fig. 3) and, secondly, that $\varepsilon_{\text{surf}}$ saturated above a certain thickness, depending on the type of the substrate. Consequently, at a given electrical power $P_{\text{el}}$ in our “new” heating system, or, at a fixed temperature of the hot plate (conventional heating system), the temperature of the glass substrate is not equivalent to that of the TCO; this will be discussed in the next section.

**Substrate temperature: measure and simulation**

Both simulations and experimental results of the substrate temperature variation during the deposition of a-Si:H film using the Hot-Wire technique and at low gas pressure will be presented. The effect of the filament radiation on the substrate (but not on the growing layer) as well as the influence of the growing a-Si:H film on the surface emissivity have both been considered in our simulations.

Two situations are analysed in the present paper, i.e. the deposition of a-Si:H on glass and on TCO (see Fig. 4). In the first case, the substrate temperature increases monotonously, this due to the decrease of $\varepsilon_{\text{surf}}$ with the thickness of the deposited a-Si:H film. However,
the saturation above ~4000Å of deposited a-Si:H is not reached, as predicted theoretically from the simulation. This effect is attributed to the absorbed part of the emitted filament radiation by the a-Si:H, which increases with the thickness of the deposited a-Si:H film.

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In the second case (i.e. deposition on TCO), we observe initially a fast increase of $T_{dep}$ due to the absorption of the filament radiation by the TCO and finally a slow decrease of $T_{dep}$ caused by the increase of $T_{surf}$. In both situations, the simulations and measurements agree well, although we neglect the contribution of the absorption of the emitted filament radiation by the a-Si:H. The changes of the substrate temperatures are also significant and very different in both situations. That has the consequence that it is difficult to simultaneously deposit identical layers on glass and on TCO as is done often to correlate film properties and solar cell performances. Similar behaviour are also observed in the case of deposition at low pressure with a conventional heating system.

**Solar cells**

Finally, the effect of the temperature variation during the deposition of the intrinsic layer incorporated into a p-i-n structure by hot-wire technique has been analysed in three situations (see Fig. 5):

- **Cell #1**: the electrical power $P_{el}$ applied to heat the substrate was set to the value (i.e. 0.4 Wcm$^{-1}$) used to obtain 270°C on glass substrate; that means we do not consider the difference of the emissivity between the glass and the TCO. Hence, the temperature before the deposition is higher than the expected value of 270°C, because the emissivity of TCO is smaller than that of the glass. Secondly, a strong increase of $T_{dep}$ up to 350°C in the initial phase of the deposition occurs, due to the absorption of the filament radiation by the TCO (the SnO$_2$ is not fully transparent in the infra-red region).

- **Cell #2**: the value of the TCO emissivity was taken into account by adjusting the electrical power to obtain 270°C prior to the deposition ($P_{el} = 0.2$ Wcm$^{-1}$). Now, the substrate temperature rises up to 300°C during the initial phase of the deposition and decreases monotonously to 270°C after.

- **Cell #3**: By adapting the electrical power, the substrate temperature was kept at a constant value of 270°C; note that the low thermal inertia of the heating system was able to compensate the fast increase of $T_{dep}$ that occurs during the initial phase of the deposition (effect of the radiation of the filament).

Table 1 summarizes the performances of the three solar cells described above. First, it has been observed that the $V_{oc}$ and the fill factor of the cell #1 are strongly reduced by the high substrate temperature during the deposition of the intrinsic layer.

<table>
<thead>
<tr>
<th></th>
<th>$V_{oc}$ [V]</th>
<th>$I_{sc}$ [mAcm$^{-1}$]</th>
<th>FF</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell #1</td>
<td>0.680</td>
<td>13.26</td>
<td>0.540</td>
<td>4.87</td>
</tr>
<tr>
<td>Cell #2</td>
<td>0.824</td>
<td>15.24</td>
<td>0.646</td>
<td>8.11</td>
</tr>
<tr>
<td>Cell #3</td>
<td>0.838</td>
<td>14.85</td>
<td>0.704</td>
<td>8.76</td>
</tr>
</tbody>
</table>

Table 1. Summary of solar cells performances obtained under different heating conditions applied during the growth of the intrinsic layer.
In cell #2, the moderate fill factor can probably also be attributed to the increase of $T_{dep}$ during the initial phase of the deposition; this hypothesis is supported by the results obtained for the cell #3, where the substrate temperature was kept constant.

Finally, it is important to evaluate the potential of improving the solar cell efficiency containing an intrinsic layer deposited by hot-wire. In the past, there has been found a strong correlation between the solar cell performance and the quality of the intrinsic layer evaluated with $\mu^0T^0$ [9]. We observe that the cell #3 is close to the correlation obtained for full PE-CVD solar cells (see Fig. 6). That means that the performance of the cell #3 is mainly limited by the quality of the intrinsic a-Si:H layer.

Fig. 6. Correlation between the intrinsic layer quality (characterised with the so-called $\mu^0T^0$ parameter) and the solar cell performance. Open symbols represent a study with an intrinsic layer deposited by PE-CVD and the circle the cell #3; the doped layers $<p>$ and $<n>$ were identical for all solar cells. Note that an increase of the deposition temperature affects the performance of the solar cell, although the quality of the intrinsic layers deposited between 220°C and 280°C by PE-CVD remains constant.

CONCLUSIONS

In the present study, the problem of keeping the substrate temperature constant during the deposition of intrinsic a-Si:H layers with the hot-wire technique at low pressure ($<10^{-1}$mbar) was considered. The radiation of the filament and the change of the surface emissivity during the growth affected strongly $T_{dep}$. We have also demonstrated that a better control of the substrate temperature during the deposition of the intrinsic layer can improve significantly the solar cell performances, especially the fill factor.

The substrate temperature in the case of solar cell with intrinsic layer deposited by hot wire is a crucial point, because the more stable materials obtained with this technique require a relatively high $T_{sub}$. However, it has been shown recently that more stable a-Si:H can be obtained at moderated $T_{sub}$, i.e. 320°C [4]; thus both a good control of the deposition temperature and a development of an anti-diffusion barrier (integrated into the $<p>$ layer) will certainly allow to realise more stable solar cells.

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REFERENCES


