ABSTRACT: We studied the absorption losses in the back ZnO layer as well as the influence of surface structure of the ZnO/silver interface on silicon thin film solar cell properties. Low absorption is one crucial factor for reflector performance. Thus, addition of oxygen to the sputter gas might be necessary to optimize reflector performance. Additionally, light scattering at the back reflector is still important, even if light scattering is already introduced by the front contact. This is demonstrated by comparison of polished and conformal silver reflector interface. Finally we indicate further potential by improvement of the silver reflectivity by high temperature growth of silver reflector. However, due to limitation of the maximum substrate temperature by the silicon p-i-n structure this improvement cannot be easily transferred to cell efficiency.

Keywords: ZnO, Sputtering, Micro Crystalline Si, Back Reflector

1 INTRODUCTION

Light trapping in silicon thin film solar cells is considered as one major factor for high efficiency. Several studies addressed the importance of light scattering and absorption losses at the front contact [1,2,3,4]. After successful optimization of the front contact properties, Berginski et al [5] showed significant potential of an improved back reflector. Typically a zinc oxide silver double layer serves as reflector. In the short wavelength region, the surface plasmon absorption of the ZnO silver interface is significant [4], but most light has been absorbed within the silicon when it arrives at the reflector. However, due to the rough interface the absorption peak extends to the long wavelength range and additionally free carrier absorption in the ZnO layer might play a role in the near infrared region (NIR). Especially here the parasitic absorption of the reflector becomes important due to the low absorbance in the silicon [5]. In this study, we address the absorption losses and light scattering of the back contact.

2 EXPERIMENTAL

Microcrystalline silicon solar cells were prepared on texture etched aluminum doped zinc oxide (ZnO:Al) films. Details on ZnO:Al properties and silicon preparation can be found elsewhere [6,7]. The back contacts were prepared by sputtering of ZnO:Al either in a vertical inline system (VISS 300, VAAT, Germany) or in a small area sputtering system supplied by J.K. Lesker, USA. The silver films were either sputtered in the latter system or deposited by thermal evaporation. For elevated substrate temperatures the substrates were heated for at least one hour before deposition.

Optical characterization of films and cells was performed by a dual beam spectrometer or photo-thermal deflection spectroscopy (PDS). Conductivity of the ZnO layers was determined by J/V measurements between two evaporated silver contacts. The solar cells were characterized by J/V measurements either in the dark or under AM1.5 illumination and additionally by differential spectral response measurements.

3 RESULTS

From previous studies we know, that absorption in the contact layers must be reduced [5]. Free carrier absorption must be present to a certain extend in the front contact as free carriers must be present to provide sufficient conductivity. At the back contact the lateral current transport is provided by the metal, thus the ZnO interlayer must not be highly conductive. To adjust the residual absorption in the ZnO:Al film we added small amounts of oxygen to the sputtering gas. Figure 1 shows absorption spectra of ZnO films prepared with different oxygen fractions in the sputtering gas. The films were deposited at room temperature on bare glass for optical and electrical characterization and on solar cells to investigate their performance. The optical characteristics were determined by PDS and from this we calculated the resulting absorption in 160 nm ZnO film which corresponds to twice the thickness of the ZnO:Al layer in front of the reflector. Even though, absorption losses in this thin layer are around 1 % small additions of oxygen can strongly reduce these losses by about two orders of magnitude at 2.5 % oxygen fraction in the sputtering gas. Higher amounts of oxygen lead to slightly higher absorption, but still far below 0.1 %. This might be related to worse film growth. However, X-ray diffraction measurements indicate larger ZnO:Al grains with increasing amount of oxygen (not shown). The conductivity stetically decreases, thus the calculated series resistance from this layer for a 1 cm² cell becomes severe at oxygen fraction above 2.5 % as indicated in Table I. Please note, that the resistance is only estimated by the assumption of an isotropic conductivity. The short circuit current and fill factor of the respective solar cells are depicted in the same table and directly confirm the observed changes in material properties. The current density is high for more transparent back ZnO films and the fill factor drops severely with increasing resistance. The effect of transparency is illustrated spectrally by the quantum efficiency QE in Figure 2. Above about 550 nm QE profits in the whole wavelength range. Thus, even above 800 nm, where hardly any absorption in the ZnO film can be directly measured, the effect in solar cells is still severe.
Table I: Conductivity and series resistance of 80 nm back contact ZnO layer of Figure 1 as well as short circuit current density and FF of μc-Si:H solar cells incorporating these ZnO films at the back reflector.

<table>
<thead>
<tr>
<th>O2/Ar (%)</th>
<th>σ (S/cm)</th>
<th>R (Ω)</th>
<th>JSC(red) (mA/cm²)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>250</td>
<td>3e-8</td>
<td>11.7</td>
<td>70</td>
</tr>
<tr>
<td>0.5</td>
<td>60</td>
<td>1e-7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>8e-4</td>
<td>0.01</td>
<td>13.2</td>
<td>69</td>
</tr>
<tr>
<td>6.3</td>
<td>8e-7</td>
<td>10</td>
<td>12.6</td>
<td>64</td>
</tr>
<tr>
<td>12.5</td>
<td>1e-10</td>
<td>800</td>
<td>12.6</td>
<td>42</td>
</tr>
</tbody>
</table>

Figure 1: Absorption of 160 nm ZnO films sputtered at different oxygen partial pressure calculated from absorption coefficient.

Figure 2: Quantum efficiency of μc-Si:H solar cells incorporating ZnO films of Figure 1 at back reflector.

In the next step we investigated the influence of surface topography at the back side. Simulation studies revealed potential improvement by a smooth reflector interface [8]. For this purpose we compared the rough back reflector interface that occurred just by conformal deposition on the rough front contact and a polished reflector. The polishing step was performed after the back zinc oxide layer. The thickness of the polished ZnO film was adjusted to achieve comparable thickness to the unpolished back contact. We peeled of the silver layer by etching and investigated the silver interface by atomic force microscopy.

Figure 3: As-deposited and polished back reflector as determined by AFM.

Figure 4: Dark J/V curve of polished and reference solar cell.

Figure 5: Quantum efficiency of polished and reference solar cell.

Figure 3 shows the resulting surface images. As can be seen, the rough interface shows the inverse structure of typical front contacts [6] and the polished one only shows some narrow grooves. The respective solar cells exhibited shunts that were removed by applying reverse voltage. The effect can easily be seen in the dark J/V curve in Figure 4. The dark current is extremely high but can be suppressed even below the current of the reference cell. The quantum efficiency (QE) measurements are shown in Figure 5. The polished cell exhibits lower QE in the whole spectrum. After shunt busting the QE can be lifted towards the unpolished cell, which indicates that the lower blue response is no optical effect. Above around 550 nm the QE curve still is below the reference value. This indicates either worse light trapping or higher absorption at the reflector interface. However, in case of strong absorption one would expect...
increased overall absorption of the cell and reduced reflection. In fact, the reflection is increased and thus worse light trapping is at least present, if it is not the only effect of the polishing.

Finally we would like to show further potential to improve the back reflector. We deposited silver by sputtering at different substrate temperature onto texture etched ZnO:Al front contact. The reflectivity of the silver surface is shown in Figure 6. The reflectivity of that model system can be improved by the high temperature by 1-1.5 % absolute in the whole spectrum. The potential for the back reflector is even higher, since the reflecting interface in the solar cells is the nucleation side of the silver and thus of lower quality than the surface of the deposited films. If this improvement could be transferred to solar cells the efficiency will be largely increased. Unfortunately, the high temperatures cannot be applied to the cells due to temperature limitations of the absorber material.

![Figure 6: Reflectivity of silver layer deposited at different temperatures onto rough ZnO:Al films.](image)

4 CONCLUSIONS

We showed the importance of low absorption and light scattering at the back reflector. The balance between transparency and resistance of the back ZnO must be adjusted to achieve high efficiency solar cells. Additionally the solar cells can suffer from light diffusion at rough silver reflector interface even though, the front contact already is textured. Still absorption losses at the reflector are severe and we showed potential to improve the silver reflectivity by about 1 % which is quite large as compared to typical absorption in the absorber layer itself. Further work has to be done to transfer the experimental results of improved silver reflectivity to solar cells.

ACKNOWLEDGEMENT

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