ABSTRACT: The development of back and front contacts for μc-Si:H thin film solar cells in a n-i-p configuration is concerned in this work. Two types of back contacts have been used on glass substrates: (i) etched ZnO layers (with the optimized texture for μc-Si thin film solar cells in p-i-n configuration) and (ii) highly reflective Ag/ZnO layers, deposited on the textured ZnO. The effects of both types of back contacts on solar cell performance will be discussed in this paper. Transparent ZnO covered by Ag grids are used as front contacts. The window layers were front ZnO and microcrystalline silicon p-layer, deposited at different trimethylboron (TMB) concentrations. The effect of front ZnO layer thickness and p-layer doping on cell performance have been investigated and correlated with electrical and optical properties of these layers, deposited on glass.

Keywords: Thin Film Solar Cell, μc-Si:H, ZnO

1 Introduction

Thin-film silicon solar cells in n-i-p configuration have the advantage that they can be used on opaque and flexible substrate materials including metal and plastic foils. In this configuration, a back contact with high reflectivity texture for light trapping is required. Several materials and structures were developed as back reflectors in the past, such as hot-Ag/ZnO, textured-plastic/Ag/ZnO and Ag/textured-TCO [1-3]. In this paper, two types of back contacts have been used on glass substrates. We start with the textured etched ZnO, which is optimized for our p-i-n solar cells [4]. This back contact together with a glass substrate has been used as a benign and reproducible standard for the optimization of the layer growth conditions. However, this back contact is transparent, so to obtain high reflection, the texture etched ZnO is covered with Ag and a thin ZnO layers. Both the ZnO and the highly reflective ZnO/Ag/ZnO substrates were used in each single deposition run for comparison.

Another challenge for thin film silicon solar cells in n-i-p configuration is to make a transparent front contact with low resistance at low temperatures. Due to the trade off between optimum resistance, transparency, and total reflection of cells, the thickness of the front ZnO has been optimized for microcrystalline silicon n-i-p solar cells.

2 Experiment

The cells were deposited on two types of substrates: glass/ZnO(textured), used as an easyhandling and standard substrate for optimisation of layers, and glass/ZnO(textured)/Ag(200nm)/ZnO(80nm) for improved light trapping (see Fig. 1). Silicon thin films were deposited by plasma enhanced chemical vapour deposition (PECVD) at a substrate temperature of 180°C in a multichamber UHV system, in the following sequence: μc-Si (n)/μc-Si (i)/μc-Si (p). For p-type and intrinsic layers a very high excitation frequency (VHF) of 94.7MHz was used. N-layers were grown at a radio frequency (RF) of 13.56MHz. Silicon films were deposited from a mixture of silane (SiH4) and hydrogen (H2) gases. Phosphine (PH3) and trimethylboron (TMB) were added to the process gas to produce n- and p-type doped layers, respectively. The deposition conditions of n-type (around 20 nm thick) and intrinsic (nominally 1 μm thick) layers were kept constant during this study. The μc-Si:H i-layers were prepared from a mixture of SiH4 and H2 gases, at the silane concentration ratio SC = [SiH4] / ([SiH 4] + [H2]) of 5.3%.

Front ZnO:Al layers, were deposited on p-layers by RF magnetron sputtering with a power of 250 W at a temperature of 150°C. Ag grids were used on top of the ZnO:Al layers. The total area of the grids for the 1 cm2 cells is 14.04 mm2.

To compare the effect of the ZnO/Ag/ZnO and ZnO back contacts on cell performance, a series of cells with varied TMB concentration (defined by the ratio of trimethylboron to silane flows, C_{TMB} = [TMB] / [SiH4]) were made on both back contacts simultaneously in each single deposition run.

Front ZnO:Al layers with varied thicknesses were also deposited on glass substrates to evaluate optical properties. The transmission (T) and reflection (R) were measured on a Perkin-Elmer photospectrometer, type lambda 950, within a spectral range from 300 to 1200 nm.
Solar cells were characterised by current-voltage (J-V) measurements under AM 1.5 illumination. During the measurements, a mask with an open area of 0.81 cm² was used for the 1 cm² cells, to avoid the collection of photogenerated carrier from outside of the cell area and also to minimize an influence of the shadowing effect during the sputter process of front ZnO.

3 Results and discussion

Fig. 2 compares the effect of ZnO and ZnO/Ag/ZnO back contact on cell performance. For the comparison, the cells were prepared with varied TMB concentrations in p-layers. The same trends can be observed for both types of back contact: with increasing C_{TMB} from 0.5 % to 1.5 %, J_{SC} and V_{OC} increase. The substantial improvement in V_{OC} (from 350 mV to 525 mV) may be attributed to an increase in conductivity of p-layers, as evident from our previous work [5], and therefore an increase in build-in potential in solar cells. For C_{TMB} > 1.5 %, V_{OC} is not further improved and J_{SC} drops slightly. The decrease in J_{SC} may result from an increase in p-layer thickness with increasing C_{TMB}, due to an enhancement of the deposition rate [6]. The fill factor (FF) is improved with increasing C_{TMB}, which may be related to the increase in the p-layer conductivity [5]. Since the Fermi level position (E_F) in the p-layers shifts towards the band edge with increasing the doping ratio, the depletion region in the p-layers gets thinner and the p/TCO contact may be improved [7, 8].

As one can see in Fig. 2, the ZnO/Ag/ZnO back reflector provides about 2 mA / cm² higher J_{SC} in comparison with ZnO back contact over the investigated C_{TMB} range. The quantum efficiency (QE) measurements [5] demonstrate that the increase of J_{SC} in the case of cells prepared with the ZnO/Ag/ZnO back contact results from improved cell response in long wavelength region of the spectrum. Since the trends obtained for the cells using ZnO back contacts are similar with those grown on ZnO/Ag/ZnO substrate, ZnO substrate can serve as a reproducible standard for the optimisation of n-i-p thin film solar cells.

Front ZnO layers (doped by 2 % Al₂O₃) have been used as window contacts in n-i-p Si thin film solar cells. As front TCO, ZnO layers are required to have high transparency and high conductivity. To investigate the effects of front ZnO on cell performance, a series of solar cells, with front ZnO thicknesses varied between 30 nm and 380 nm, was studied. The effect of the front ZnO thickness on the cell performance is shown in Fig. 3. In these solar cells, simple textured ZnO was used as a substrate and C_{TMB} of the p-layers was kept constant at 1.5 %. It is seen that V_{OC} is not much affected by the value of the front ZnO thickness, while FF is improved from 68.5 % to 72 % with increasing the ZnO thickness from 30 nm to 155 nm and then saturates. The most significant effect of front ZnO thickness is observed in J_{SC}. The J_{SC} is influenced so significantly, that the observed trend in efficiency follows the trend in J_{SC}. The J_{SC} vs. ZnO thickness curve has a sinusoidal-like shape, with the maximum J_{SC} of 19 mA / cm² at the thickness of 70 nm and the second maximum J_{SC} (17 mA / cm²) at the...
The thickness of 240 nm.

The optimal front ZnO thickness is found to be 70 nm, which is comparable with reported by others [9]. A solar cell prepared on a ZnO/Ag/ZnO back reflector with 70 nm thick front ZnO shows a high conversion efficiency of 8.25% with a high J SC of 21.3 mA/cm² for 1 µm thick i-layer (see Fig. 3).

Fig. 4 shows the effect of ZnO thickness on the sheet resistance for the ZnO layers prepared on glass. A significant decrease in the sheet resistance from 600 Ω to 50 Ω can be seen with increasing the thickness from 30 nm to 155 nm. The decrease in the sheet resistance of ZnO layer may result in the increase in the FF of solar cells, made with these ZnO as front contacts, as shown in Fig. 3.

The changes in J SC with the front ZnO thickness could be attributed to the effects of parasitic absorption in the front ZnO or/and in the total reflection (R total ) of the solar cells. Fig. 5 shows the absorption of the ZnO layers on glass with thicknesses of 30, 70, 155 and 240 nm and the results of the total reflection measurements for the solar cells fabricated with these ZnO layers as front contacts.

A slight increase in the absorption of the ZnO layers can be seen with increasing the ZnO thickness, at the wavelengths below 500 nm and above 800 nm. At the wavelengths between 500 nm and 800 nm, the ZnO layers with the thicknesses of 70 nm, 155 nm and 240 nm have similar absorption, which is a little (around 1.5%) higher than the absorption of the 30 nm thick ZnO layer.

On the other hand, one can see in Fig. 5 that the total reflection of the solar cells is significantly influenced by the thickness of front TCO, particularly at the wavelength region between 400 nm to 800 nm. The 70 nm thick front ZnO results in the lowest total reflection. The lowest total reflection value of nearly 3% is obtained with the 70 nm front ZnO at the wavelength of around 560 nm. The 155 nm thick front ZnO leads to a sinusoidal-like curve of the total reflection versus the wavelength, with the highest R total of close to 30% at the wavelength of around 500 nm and the lowest R total of about 3% at the wavelength of 640 nm.

For the front ZnO layers investigated here, the effect of the thickness on the total reflection of solar cells is much stronger than the effect of absorption in ZnO layers. It suggests that the variations in J SC with front ZnO thickness may largely be related to the total reflection loss of solar cells. It is in agreement with our results presented in Fig. 3 and Fig. 5.

The variations in cell reflection with front ZnO thicknesses can be explained by the antireflection effect. The first requirement for an anti-reflection coating on silicon [10] is:

\[ n_{\text{AR}} = \sqrt{n_{\text{air}} \cdot n_{\text{Si}}} \]  

where \( n_{\text{AR}} \) is the refractive index of the anti-reflection coating, \( n_{\text{air}} \) and \( n_{\text{Si}} \) are the refractive indices of air and silicon, respectively. The front ZnO layer with a refractive index of around 2 may provide an antireflection coating, since \( n_{\text{Si}} \) is close to 4. Another requirement for an anti-reflection coating is that the relative phase shift between the two reflected beams on the air-ZnO and ZnO-Si interfaces is 180°, to obtain a destructive interference. For a perpendicular incident light, the thickness of an anti-reflection coating should be:

\[ d = \frac{n_{\text{AR}}}{4n_{\text{AR}}} (n = 1, 3, 5, 7, \ldots) \]  

Therefore, the 70 nm thick ZnO can result in an anti-reflection effect at a wavelength of 560 nm, whereas the 240 nm thick ZnO at a wavelength of 640 nm. This is in excellent agreement with our results presented in Fig. 4.

7 Summary
- Two types of back contacts ZnO (textured) and ZnO/textured/Ag/ZnO have been used in µ-Si thin film n-i-p solar cells. The highly reflective ZnO/Ag/ZnO
back contact results in about 2 mA/cm² higher $J_{SC}$ than the “simple” ZnO back contact. The trends in J-V characteristics, obtained for the cells using ZnO back contacts are reproducible with those grown on ZnO/Ag/ZnO. Thus ZnO back contacts can serve as a reproducible standard for certain developments of the n-i-p solar cells.

- The effects of the ZnO thickness on the cell performance have been investigated. The optimal front ZnO thickness of 70 nm is obtained. The variations in $J_{SC}$ with front ZnO thickness are linked with total reflection of the solar cells. The cell prepared with optimal front contact thickness and highly reflected ZnO/Ag/ZnO back contact, shows high $J_{SC}$ of 21.3 mA/cm² and a high conversion efficiency of 8.25% for 1 µm thick absorber layer.

- Electrical and optical properties of ZnO layers grown on glass have been investigated. The increase in FF of the solar cells with increasing the thickness from 30 nm to 155 nm may result from the significant decrease in the sheet resistance of ZnO layers as front contacts.

4 References