ABSTRACT: With decreasing absorber layer thickness, the efficiency of a-Si:H/µc-Si:H tandem solar cells decreases due to the decreased lower absorption. Nevertheless, such thin devices have considerable advantages regarding production costs, electrical properties and stability. In order to improve the generated photo-current of such thin tandem cells, the surface morphology should be optimized for that specific case. In order to tap this potential, a variation of the standard texture-etched ZnO:Al front contact with much smaller feature sizes is applied in thin tandem cells, which leads to a considerable improvement in photo-current. An a-Si:H/µc-Si tandem cell with a total silicon thickness of only 600 nm (for which the deposition time of the absorber layers is 22 minutes in total) on a high rate texture-etched ZnO:Al (with a deposition time of only 2 minutes) was obtained with an initial efficiency of 9.4%.

Keywords: amorphous silicon, microcrystalline silicon, TCO, zinc oxide, deposition rate, light trapping.

1 INTRODUCTION

In the past years the development of thin-film silicon multi-junction devices has led to initial conversion efficiencies up to 15% for small cells on lab scale [1,2]. At the same time, module efficiencies up to 10% have been reached in production processes. Several approaches are investigated in order to reduce the production costs such as high-rate deposition of microcrystalline silicon (µc-Si:H) [3,4], high-rate deposition of the aluminum doped zinc oxide (ZnO:Al) front contact [5], deposition of amorphous silicon (a-Si) and µc-Si absorber layers under high base pressure conditions or with process gases of low purity [6,7], deposition on cheap flexible substrates [8,9], and significant reduction of the thicknesses of intrinsic layers [10]. Depending on the degree in which these approaches are applied, they all lead to a certain reduction in device performance, as it can be seen for the reduction of absorber layer thickness in Figure 1.

![Figure 1. Thickness dependency of a-Si:H/µc-Si:H cell efficiency in near-matched cases [10].](image)

It is seen that the efficiency of very thin a-Si:H/µc-Si:H tandem cells is lower compared to thicker ones, which is due to a decrease in short-circuit current density. On the other hand, these thin devices have a number of important advantages: the production times are much shorter, the material consumption is lower, the electrical properties are better (open circuit voltage and fill factor), and they are more stable against light-induced degradation. In this paper, we demonstrate that the reduction in short-circuit current density can be reduced when a TCO with a smaller feature size than standard is applied.

2 EXPERIMENTAL DETAILS

Tandem solar cells based on a-Si and µc-Si absorber layers have been deposited on texture-etched ZnO:Al coated glass. Two different types of tandem cells with a high rate ZnO:Al front contact and a standard ZnO:Al front contact as reference were deposited. The standard ZnO:Al films [12] were sputtered from planar ceramic target (1 wt% Al2O3) in radio frequency (RF) mode with a deposition rate of around 6 nm/m/min. Additionally, high-rate ZnO:Al was deposited at a rate of > 100 nm/m/min from rotatable dual magnetron (RDM) cathodes with ceramic ZnO targets (0.5 wt% Al2O3). The system was operated in MF (medium frequency) sputtering mode with an excitation frequency of 40 kHz for all high-rate ZnO:Al depositions. The discharge power was 14 kW, which corresponds to a power density of about 10 kW/m² [5]. This power density still provides potential for higher rates. The texture etch process consisted of a 30 s and 50 s dip in 0.5% HCl at room temperature for the RF and MF films, respectively. The sheet resistance R after etching was less than 8 Ω□ for all films.

The active silicon layers were deposited with a Plasma-Enhanced Chemical Vapor Deposition (PECVD) process in a 30 x 30 cm² reactor. The a-Si:H absorber layer of the top cell was deposited at standard conditions at an excitation frequency of 13.56 MHz, leading to deposition rates of 0.15 nm/s. The µc-Si absorber layers of the bottom cells were deposited with a high deposition rate of 1 nm/s using an excitation frequency of 40 MHz in the same PECVD system.

ZnO/Ag back contact pads define a test cell area of 1 cm². IV characteristics of the solar cells were measured at 25°C under illumination at AM1.5. The quantum efficiency was determined in the spectral range from 300 to 1100 nm without bias voltage. During the measurement of the top cell with a chopped probe beam, the bottom cell was selectively saturated with DC bias light and vice versa to characterize each cell individually.
3 RESULTS AND DISCUSSION

3.1 Deposition times

The following approaches to reduce the deposition rate are combined:

A) Texture-etched ZnO:Al films sputtered from rotatable dual magnetrons (RDM) were applied as transparent front electrode. The < 800 nm thick films were deposited in a dynamic quasi-in-line process at high deposition rates > 100 nm·m/min.

B) Very thin active amorphous and microcrystalline silicon layers of the a-Si/µc-Si tandem cells were applied. Usually, the optimum in device performance is found at a total absorber layer thickness of around 2 µm or thicker [4, 11]. Here, we focus on cells that are 3 times thinner in order to benefit from the expected shorter deposition times, lower material consumption, better electrical devices properties and higher stability [10].

C) The µc-Si absorber layer is deposited at an increased deposition rate of 1 nm/s [4].

3.2 Properties of high-rate ZnO:Al

In Figure 2, the surface morphology of standard texture-etched ZnO:Al is shown (left) compared to texture-etched high-rate ZnO:Al. It can be seen that the morphology is much smaller for the high rate front contact. The surface morphology is analyzed in more detail in the following. It should be remarked that the surface topography of the high-rate ZnO:Al film differs from that of previously published RDM films [5]. The smaller feature size could make the high-rate ZnO an interesting candidate for application in thin tandem cells.

Figure 2. AFM surface morphology images of standard ZnO:Al (left) und high-rate ZnO:Al.

Figure 3 shows sketches of the cross sections of thin tandem cells for standard and high rate ZnO, when conformal growths of the silicon layer are assumed. It can be seen that feature heights for the standard ZnO:Al are comparable to the cell thickness, whereas feature sizes for the high rate ZnO:Al are obviously smaller.

In Figure 4 and 5, the height distribution and the distribution of reciprocal lateral feature sizes are given. These data confirm the observed differences. The root mean square roughness \( \delta_{\text{rms}} \) for the standard ZnO:Al is 136 nm whereas for the high rate ZnO:Al it is only 58 nm. For the standard ZnO:Al the typical lateral feature size is 2.0 µm, whereas for the high-rate ZnO:Al it amounts 1.2 µm. Using the model by Dominé et al. [13], the haze at the ZnO/Si interface is calculated based on the AFM data for a wavelength of 700 nm. This results in a haze of 0.97 and 0.54 for the standard and high-rate ZnO:Al, respectively.

Figure 3. Sketches of cross-sections of 600 nm thick tandem cells based on AFM data for standard ZnO:Al (left) and high-rate ZnO (right). It is assumed that the silicon is conformally deposited.

Figure 4. Histogram of feature heights for the standard (black) and high-rate (red) ZnO:Al front contact.

Figure 5. Distribution of reciprocal lateral feature sizes for the standard (black) and high-rate (red) ZnO:Al front contact.

3.3 Device Performance

On standard texture-etched ZnO:Al, thin tandem cells were prepared with a total thickness < 600 nm by reducing the thicknesses of the intrinsic layers such that the generated currents in top and bottom cell were similar. As bottom cell absorber layer high-rate µc-Si:H was applied with a deposition rate of 1 nm/s. The deposition time of the bottom cell was less than 7 minutes.

With reduced i-layer thicknesses, a cell with a total silicon thickness of 600 nm was made on the standard ZnO:Al. It delivered an efficiency of 9.3%, as depicted in
Figure 6. A series was made in order to vary the relative top and bottom cell thicknesses in order to satisfy the current matching condition. The deposition time of the top cell was 15 minutes by which a total i-layer deposition time of less than 22 minutes was achieved.

The same a-Si:H/µc-Si:H layer stack (from the same deposition system) on the high-rate ZnO:Al showed a considerable increase in short-circuit current density and a slight reduction in fill factor and open-circuit voltage. Effectively, the efficiency was slightly increased by 0.1% absolute.

In Figure 7, a thin tandem cell with optimized TCO/p interface is compared to a tandem cell of standard thickness by means of cell reflectance and external quantum efficiency (EQE). Both cells were deposited on both types of ZnO. It is shown in Figure 7 that the high-rate ZnO improves the current for the thin tandem cell over a broad wavelength range. For standard tandem cells, however, the short-circuit current density even decreases considerably. The cell reflection data in Figure 7 show that for the thicker tandem cell, the differences in EQE correspond to the differences in reflection, which indicates that the higher current density for the high-rate ZnO:Al result from an improved light trapping.

For the thin tandem cell, however, the EQE improved in spite of a slight increase in cell reflectivity. This indicates that the application of high-rate ZnO:Al leads to a decreased parasitic absorption. The reduced parasitic absorption could be explained by the lower Al concentration in the RDM targets. Apparently, the thin tandem cell is much more sensitive to this difference compared to the thicker one.

3 CONCLUSIONS

Thin-film a-Si:H/µc-Si:H solar cells have been prepared by using high deposition rates for the front contact as well as for the silicon absorber layers. Additionally, thin active layers (only 600 nm in total) have been used. The total intrinsic layer deposition time was only 22 minutes.

It is observed that thin a-Si:H/µc-Si:H tandem cells on high-rate ZnO:Al front contacts, which show smaller feature sizes, show a better performance compared to cells on standard lab-type ZnO substrates. An initial efficiency of 9.4% was obtained for test cells. The gain in short-circuit current density is related to an improved light trapping of the high-rate ZnO:Al for thin tandem solar cells.

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