ULTRA-SHORT DEPOSITION TIMES FOR a-Si/µC-Si TANDEM CELLS ON TEXTURE-ETCHED ZnO:Al

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ABSTRACT: In this paper we explore the efficiency potential of a-Si/µc-Si tandem cells that are produced under conditions that lead to a considerable production cost reduction. On standard lab-type texture-etched ZnO:Al, 1 cm² a-Si:H/µc-Si:H tandem test cells on a deposition area of 30 x 30 cm² were made that showed an initial efficiency of 9.9%, whereas the total deposition time of intrinsic layers was only 22 minutes. The silicon thickness is only 600 nm. On high-rate texture-etched ZnO:Al an efficiency of 9.4% initial was reached. Standard light-induced degradation experiments showed a degradation rate of only 5 to 8% after 1000 hours. The regime of very short preparation times and relatively high stabilized efficiencies is relevant for production.

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.

Here, we explore the efficiency potential of a-Si/µc-Si tandem cells that are produced under conditions that lead to a considerable production cost reduction. On deposition area of 30 x 30 cm² with industrially relevant processes, the following approaches 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 tandems 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 a high deposition rate of 1 nm/s [4].

2 EXPERIMENTAL METHODS

Tandem solar cells based on a-Si and µc-Si absorber layers have been deposited on texture-etched ZnO:Al coated glass.

As a reference, 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 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 Rₛ 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 30x30 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 test cell area of 1 cm². IV characteristics of the solar cells were measured at 25 °C under illumination close to 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.

3 RESULTS AND DISCUSSION

3.1 Properties of high-rate ZnO:Al

Figure 1 shows that the ZnO:Al deposited with the RDM cathodes becomes more resistive with increasing deposition rate. With a power of 14 kW, corresponding to a deposition rate of 100 nm·m/min, the resistivity of the as-deposited film amounts 5.4·10⁴ Ω·cm. After the wet-chemical etching process the surface of the high-rate ZnO:Al films exhibits a root mean square (rms) roughness of only 58 nm. For etched standard rf-ZnO:Al films typically a higher rms roughness of 130-150 nm is achieved. Consequently, the haze, which is the quotient of diffuse and total transmission, of the high-rate ZnO is lower than of the RF-ZnO (see Figure 2). The total transmission of the high-rate ZnO shows weak but
noticeable interference fringes, which typically appear for samples with reduced light scattering ability. All in all the total transmission of the high-rate ZnO is higher than that of the standard (RF) ZnO. The reason is the reduced Al$_2$O$_3$ content of the tube targets (0.5% wt. compared to 1% wt.). The surface topography of the presented films differs from that of previously published RDM films [5].

**Figure 1:** ZnO:Al resistivity in as deposited state as a function of discharge power. The deposition rate scales linearly with discharge power. At 14 kW a deposition rate of 100 nm•m/min was reached.

**Figure 2:** Total (dotted lines), diffuse transmission (dashed lines) and haze (full lines) of texture etched high-rate ZnO:Al films (blue lines) in comparison with standard rf-ZnO:Al films (red lines) sputtered at low discharge power.

### 3.2 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 and an efficiency of 9.3% was made. Here, a series was made in order to vary the relative top and bottom cell thicknesses in order to satisfy the current matching condition. Moreover a series of tandem cells was made in which the silane concentration during the deposition of the bottom cell was varied in order to optimize the phase mixture of the material. 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 IV curve and derived parameters are given in Figure 3 (thin solid curve). The belonging quantum efficiency curves and calculated currents from top- and bottom cell are given in Figure 4 (thin solid curve). It is seen that the cell is slightly bottom cell current limited, which is de-sired from the stability point-of-view. The fill factor (FF) of 74.6% and Voc of 1420 mV are significantly higher compared to thicker standard tandems (where typical values of 73% and 1350 mV are found [10]). This can be attributed to the smaller thicknesses of the intrinsic layers.

The thin tandem cell was also deposited on the high-rate ZnO:Al. It is observed that Voc and FF are slightly lower but Jsc is considerably higher. As a result, the initial efficiency is higher than for the standard ZnO: 9.4% (see Figure 3, dashed line). The increase in current is confirmed by the spectral response measurements: A gain is observed over the whole spectral range and the top and bottom cell current are almost equal (see Figure 4, dashed lines). The higher current achieved on high-rate ZnO:Al demonstrates that haze is not a suitable quantity to predict the photocurrent generated in the silicon solar cells.

So far, the doped layers were unchanged starting from the standard 2 µm thick tandem cell. It is speculated that thinner i-layers allow thinner doped layers for maintaining the electrical field over the absorber layer. The doped layers were optimized for the tandem on the standard ZnO:Al, which led to an increase in efficiency from 9.3 to 9.9% (see Figure 3, thick solid line). The Voc kept constant, FF decreased slightly and Jsc increased due to the reduced parasitic absorption in the doped layers. The total silicon thickness reduced from 600 to 550 nm. The spectral response data show a gain over the whole spectral range, (see Figure 4, thick solid line). The total device thickness (including front and back contact) is only less than 1.5 µm. The initial conversion efficiency obtained with the standard ZnO:Al was 9.9% for a 1 x 1 cm$^2$ test cell. Compared to a-Si/µc-Si tandem cell with standard thickness and standard deposition rate
this is around 16 % less efficiency for a thickness reduction of 57 % and a reduction in absorber layer deposition time of 80 %. The efficiency of 9.4 % on the high-rate ZnO (without optimized doped layers) corresponds, compared to a standard tandem, to a 20 % loss in efficiency for a preparation time reduction of more than 90 % for absorber layer and ZnO deposition. Due to the thin top cells, the degradation rate is expected to be fairly low.

The degradation rate of the 550 nm thick tandem cell with optimized doped layers (large closed circles in Figure 5) is below 6 %, which led to an efficiency as high as 9.4 % after 1000 hrs degradation. The improved stability confirms the quality of the doped layers that were optimized especially for these thin tandem cells.

The overall low degradation rates are attributed to the thin intrinsic layers leading to higher electrical fields over the i-layers due to which less recombination events take place. A-Si:H/µc-Si:H tandem cells of standard thickness show degradation rates of 15 % or more after 1000 hrs of light soaking.

3 CONCLUSIONS

Thin-film a-Si:H/µc-Si:H solar cells have been prepared by using high deposition rates and thin active layer thickness (three times thinner than standard). It appeared that when using thin i-layers, there is no additional negative influence of higher µc-Si deposition rates on the device performance, due to which the production times can be further decreased. Compared to standard device thickness, the thin tandem cells show significantly less light-induced degradation. As an example, a cell with a silicon thickness of only 550 nm reaches an efficiency as high as 9.4% after 1000 hours of degradation. The total intrinsic layer deposition time is only 22 minutes.

Furthermore, it is observed that thin a-Si:H/µc-Si:H tandem cells on high-rate ZnO-Al front contacts sputtered from rotatable dual magnetron cathodes show similar performance to cells on standard lab-type ZnO substrates. This leads to a second, additional gain in preparation time without deterioration in device performance.

These observations make a-Si:H/µc-Si:H tandem cells with a total silicon thickness of < 600 nm of special technological interest.

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REFERENCES


