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Electrically flat/optically rough substrates for efficiencies above 10% in n-i-p thin-film silicon solar cells

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ABSTRACT

Substrates with extremely low roughness to allow the growth of good-quality silicon material but that nevertheless present high light trapping properties are presented. In a first application, silver reflectors are used in single and tandem-junction amorphous silicon (a-Si:H) solar cells. High initial (**stable**) efficiencies of 10.4 % (**8.1 %**) for single-junction a-Si:H cells on glass and 11.1 % (**9.2 %**) for tandem-junction a-Si:H/a-Si:H cells on plastic are obtained. A second application better suited to multi-junction solar cells based on microcrystalline silicon (μc-Si:H) solar cells is presented: the substrate consists of rough zinc oxide (ZnO) grown on a flat silver reflector which is covered with a-Si:H; polishing of this structure yields an a-Si:H/ZnO interface that provides high light scattering even though the cell is deposited on a flat interface. We present results of ~ 4-μm-thick μc-Si:H solar cells prepared on such substrates with high open-circuit voltages of 520 mV. A large relative efficiency gain of 20% is observed compared to a co-deposited cell grown directly on an optimized textured substrate.

INTRODUCTION

Poor electronic transport requires thin active layers in thin-film silicon solar cells. This leads to insufficient absorption of light in the red part of the solar spectrum. To improve light absorption and cell short-circuit current density (J_{sc}), the most used approach is to scatter light at textured interfaces, which are obtained by growing the solar cell on a textured substrate [1,2,3,4]. However, several studies have shown that deposition of thin-film silicon solar cells on textured substrates decreases open-circuit voltage (V_{oc}) and fill factor (FF) compared to reference cells deposited on flat electrodes, both for amorphous silicon (a-Si:H) [5,6] and for microcrystalline silicon (μc-Si:H) [7,8] solar cells. In this contribution, we present different types of substrates—suitable either for a-Si:H or for μc-Si:H solar cells—that are physically flat to allow for high V_{oc} * FF products while being optically rough for increased J_{sc}.

First, substrates coated with silver (Ag) with very low roughness (σ<19 nm) and haze, but with angular scattering properties comparable to a Lambertian scatterer as measured in air, will be presented. The conclusions drawn from the analysis of these substrates allows us to identify dedicated substrates for high initial and stable efficiencies both for single-junction n-i-p a-Si:H cells grown on glass and for tandem-junction a-Si:H/a-Si:H cells grown on plastic substrates textured by nano-imprinting.

Second, we use thick μc-Si:H p-i-n solar cells (~ 3.8 μm of intrinsic layer) to illustrate the potential of a substrate with a rough "buried" optical interface for efficient light scattering and a physically flat interface obtained by chemical mechanical polishing that allows for the growth of material with excellent quality. These substrates were already investigated by Sai et al. [9] and by our laboratory [10]. The high V_{oc} (520 mV) and the large efficiency increase (20%) compared to a textured reference cell demonstrate the high potential of this polished substrate for high-efficiency solar cells. We believe that these substrates will be most advantageous in n-i-p multi-junction solar cells.

EXPERIMENTAL DETAILS

Substrates and deposition of single-junction n-i-p a-Si:H cells on glass

Substrates with low roughness were made by sputtering Ag layers onto glass at moderate substrate temperature (≈150 °C). The roughness of the substrates is determined by the thickness of the Ag layer and was measured by atomic force microscopy. Flat substrates were obtained by sputtering the Ag layer at room temperature. On top of these substrates we sputtered an additional, thin aluminum-doped zinc oxide (ZnO:Al) layer. Subsequently, a single-junction a-Si:H solar cell with intrinsic layer (i-layer) thickness of ≈240 nm was deposited as described in refs. [11,12]. For the front contact, a 2.5-µm-thick boron-doped ZnO (ZnO:B) layer grown by low-pressure chemical vapor deposition (LP-CVD) was used.

Substrates and deposition of tandem-junction n-i-p a-Si:H/a-Si:H cells on plastic

Plastic substrates made of 125-µm-thick polyethylene-naphthalate were textured by UV nano-imprinting, as described in refs. [13,14]. The imprinted texture was covered by a sputtered Ag/ZnO:Al back reflector. A tandem-junction a-Si:H/a-Si:H solar cell with a bottom (top) cell i-layer thickness of ≈360 nm (≈70 nm) was deposited. The front contact was made by sputtering a 60-nm-thick indium tin oxide (ITO) layer which also acts as an anti-reflective layer.

Substrates and deposition of p-i-n single-junction µc-Si:H cells on glass

Glass substrates were coated by sputtering with a thin chromium (Cr) layer, a flat Ag reflector and a thin ZnO:Al layer. On top of this stack, 2.5 µm of non-intentionally doped (n-i-d) LP-CVD ZnO was deposited, followed by deposition of a-Si:H to create the optically rough a-Si:H/ZnO interface shown in fig. 1 (a). A physically flat interface was subsequently created by chemical mechanical polishing (CMP) (fig. 1 (b)).

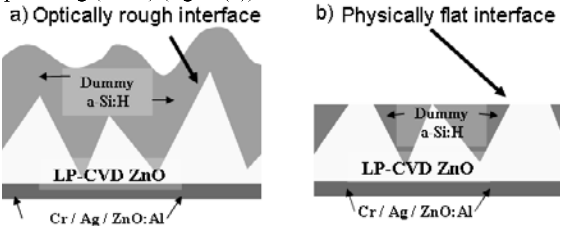

Figure 1: (a) An optically rough interface was created by deposition of a-Si:H on n-i-d LP-CVD ZnO (b) A physically flat interface was then created by CMP.

We also used a reference textured substrate to compare cell performances, which consisted of glass coated by sputtering with a thin Cr layer, a flat Ag reflector and a ZnO:Al layer onto which 5 µm of n-i-d LP-CVD ZnO was deposited. This substrate was then treated by plasma to obtain an optimal texture for the overall cell efficiency [7].

On top of these two types of substrate we deposited p-i-n µc-Si:H solar cells with an i-layer thickness of 3.8 µm. The front contact was a 5-µm-thick LP-CVD ZnO:B layer.

Measurements

The V_{oc} and FF of the solar cells (≈ 0.25 cm^2) were characterized by current-voltage measurements using a dual-lamp solar simulator in standard test conditions. The J_{sc} was obtained by the convolution of the external quantum efficiency (EQE) and the AM 1.5G solar spectrum. The EQE of each sub-cell in tandem junction a-Si:H/a-Si:H cells was measured with a positive electrical bias of 0.5 V to compensate the negative bias induced by the other sub-cell, which was saturated with light during the measurement. The total and diffuse reflectance (TR and DR) of the cells were studied using a dual-beam spectrophotometer equipped with an integrating sphere. Angular resolved scattering (ARS) measurements at a wavelength of 543 nm of selected substrates were performed. The maximum of the sinus-weighted ARS spectra were normalized to 1 in order to obtain the sinus-weighted angular distribution function (ADF) of the substrates.

RESULTS AND DISCUSSION

Single-junction n-i-p a-Si:H cells on glass

Figure 2 presents the EQE and electrical parameters of single-junction a-Si:H solar cells deposited on glass/Ag substrates with low roughness. The roughness is also indicated in fig. 2. It can be observed that the roughness of these substrates does not affect cell V_{oc} and decreases the FF by only 1% for the rougher substrates. At the same time a large gain (+13% relative) in J_{sc} can be observed.

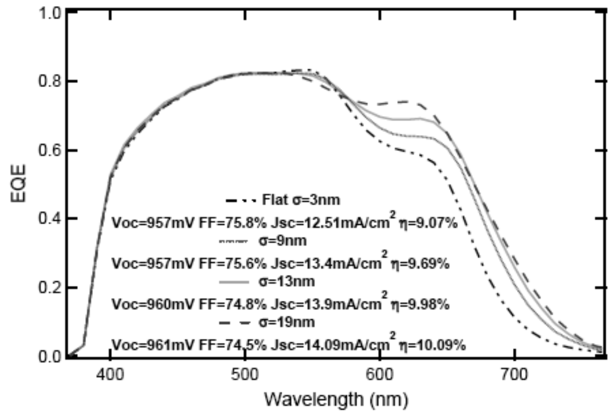

Figure 2: EQE and electrical parameters (initial state) of single-junction a-Si:H solar cells deposited on extremely smooth substrates. The roughness σ of the substrates is also indicated.

The J_{sc} increase is surprisingly high for substrates with such low roughness and low DR, which is shown in fig. 3 (a). This remarkable increase is attributed to two effects: first, the ratio of DR to TR is much higher at the Ag/Si interface in the cell than what is measured in air; and second, the angular scattering properties are excellent, corresponding closely (in air) to Lambertian scattering, as fig. 3 (b) shows.

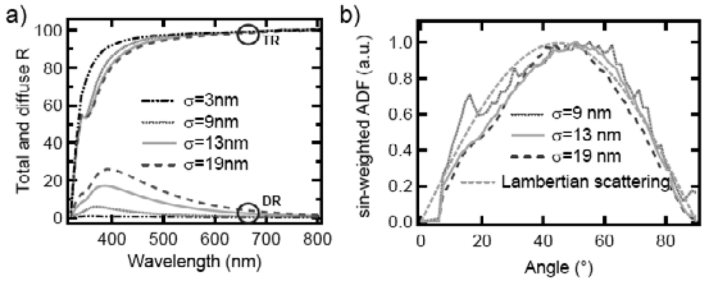

Figure 3: Optical properties of silver reflectors on glass measured in air: (a) TR and DR, and (b) sin-weighted ADF of scattered light, the sin-weighted ADF of a Lambertian scattering was added for comparison.

Best single-junction n-i-p a-Si:H cell on glass

Figure 4 displays the EQE and electrical parameters of our best cell single-junction n-i-p a-Si:H cell on glass. This solar cell was obtained on a substrate with a sputtered Ag layer deposited at a substrate temperature around 200 °C. This substrate possesses a slight advantage in light trapping over the ones presented above and still allows for very high V_{oc} and FF values. The differences in initial electrical parameters with the cells shown above can be explained by the use of a thicker, oxygenated p-doped layer. In ref. [12], a thicker silicon oxide (SiO_x) p-layer was shown to increase V_{oc} and to decrease FF, which is exactly what is observed here.

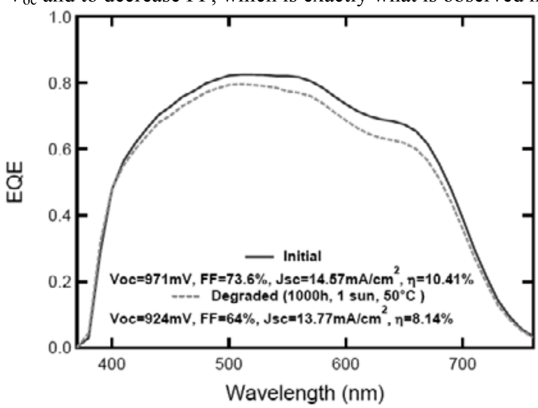

Figure 4: EQE and electrical parameters for the best single-junction n-i-p a-Si:H solar cell in initial and degraded states.

Tandem-junction n-i-p a-Si:H/a-Si:H cells on plastic

To achieve higher stable efficiency on plastic substrates, tandem-junction a-Si:H/a-Si:H solar cells were deposited on nano-imprinted reflectors. The ITO front contact forced us to use a rougher substrate than that used in the single-junction a-Si:H cells shown above. Indeed it was observed that with a conformal front contact, the rear texture becomes crucial for reaching high

J_{sc} [3]. The roughness used here was still reasonable, with σ≈50 nm. Still, this substrate cannot be considered as an electrically flat substrate. The best cell had an initial efficiency of 11.1% (V_{oc}=1.839 mV, FF=73.5%, J_{sc}=8.22 mA/cm^2) and stabilized at 9.2% as depicted in fig. 5.

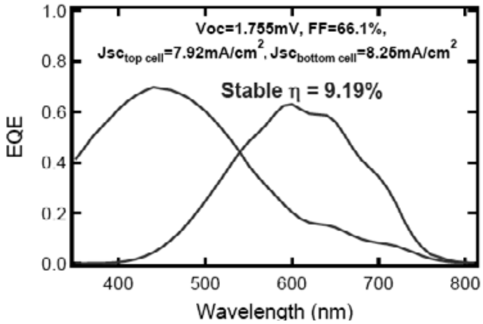

Figure 5: EQE and electrical parameters of the best stabilized tandem a-Si:H/a-Si:H solar cell.

4-μm-thick p-i-n single-junction μc-Si:H cells on polished substrates

Table 1 presents the results of co-deposited solar cells on a reference textured substrate and on a polished substrate with an optically rough but physically flat interface for cell growth. The improvement in V_{oc} and in FF on the polished substrate is directly related to an improvement in the quality of the μc-Si:H i-layer. The observed loss in J_{sc} is attributed to reflection and refraction that occurs at the flat interface areas between the ZnO and μc-Si:H layers where the ZnO pyramid tips were polished off.

Table 1: Results for co-deposited μc-Si:H cells with μc-Si:H p-doped layers.

Type of substrate	FF (%)	V_{oc} (mV)	J_{sc} (mA/cm^2)	Efficiency (%)
Textured	58	494	28.0	8.0
Polished	67	520	27.3	9.5

In order to make a fair comparison to the regular textured substrate, we also deposited the same cell on the textured substrate using an optimized p-doped layer containing oxygen. This SiO_x p-layer was shown to decrease the sensitivity of the V_{oc} and FF to the growth of the μc-Si:H cell on textured substrates [15]. Accordingly, on the textured substrate the FF increased up to 62%, the V_{oc} was stable, and the J_{sc} increased, leading to an enhanced cell efficiency of 8.7%. Still, the cell grown on the polished substrate presented in table 1 have a large advantage in FF, V_{oc} and efficiency when each cell is optimized for each specific substrate.

An extended study of these substrates can be found in ref. [10].

CONCLUSIONS

We presented substrates with low roughness (electrically flat) that allow the growth of high-quality silicon material, as proven by the high V_{oc} and FF obtained on all substrates. At the same time all substrates are sufficiently optically rough for high J_{sc} enhancement.

The substrates dedicated to single-junction a-Si:H showed that low DR measured in air is not a determining factor for interpreting J_{sc} enhancement, and that more attention should rather be paid to the substrate ADF. This understanding allowed us to develop dedicated substrates for single and tandem-junction based on a-Si:H. We obtained high initial (**stable**) efficiencies of 10.4% (**8.1%**) for single-junction a-Si:H cells on glass and 11.1% (**9.2%**) for tandem-junction a-Si:H/a-SiH solar cells on plastic.

A novel type of substrate—best suited to thick and multi-junction μc-Si:H-based solar cells—showed promising results on thick single junction μc-Si:H with a large relative gain in efficiency compared to a cell grown on a textured reference substrate. This novel type of substrate is composed of a double architecture with an optically rough "buried" interface and a physically flat surface onto which the solar cell was deposited.

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