Sol–gel coatings for light trapping in crystalline thin film silicon solar cells

R. Brendel a,*, A. Gier b, M. Mennig b, H. Schmidt b, J.H. Werner c

a Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, D-70569 Stuttgart, Germany
b Institut für Neue Materialien GmbH, Im Stadtwaldgebäude 43, D-66123 Saarbrücken, Germany
c Institut für Physikalische Elektronik, Universität Stuttgart, Pfaffenwaldring 47, D-70569 Stuttgart, Germany

Abstract

An increase of light absorption by light trapping is a key issue for the design of thin film solar cells from crystalline silicon. According to our numerical work, the deposition of crystalline silicon layers of thickness, $W = 4 \ \mu m$, on textured glass substrates doubles the cell current for facet angles, $\alpha = 75^\circ$, and texture periods, $p < 16 \ \mu m$, without the need for anti-reflection coatings. We demonstrate the fabrication of such micron-sized light traps by embossing of sol–gel glasses. © 1997 Elsevier Science B.V.

1. Introduction

Increase of optical absorption by light trapping schemes becomes vital for thin polycrystalline silicon (c-Si) solar cells. The mechanisms of light trapping in c-Si solar cells are well understood [1,2]. Conventional thick cells are fabricated from Si wafers of thickness $200 \ \mu m < W < 400 \ \mu m$ and are commonly textured with pyramids of period $10 \ \mu m < p < 20 \ \mu m$, hence $p \ll W$. Very thin cells with thickness $2 \ \mu m < W < 5 \ \mu m$ would require sub-micron-sized textures to fall in the category $p \ll W$. Alternatively, the thin semiconductor layer can be deposited onto a substrate that is coarsely textured with a structure of period $p > W$ [3]. This approach provides excellent light trapping [4–7]; especially if the texture period $p$ has the same order of magnitude as the thickness $W$ [5–7]. Then, textures with periods $p = 10 \ \mu m$ are required for c-Si films of thickness $2 \ \mu m < W < 5 \ \mu m$. To our knowledge the fabrication of such micron-sized textures into glass has not yet been demonstrated.

Sol–gel techniques promise an elegant way to fabricate micron-sized textures. Embossing allows one to form a wide variety of texture geometries. Therefore, this paper evaluates different texture geometries by numerical ray tracing in order to identify effective light trapping schemes. Then we describe the formation of one of those geometries by the sol–gel method.

2. Theoretical and experimental procedures

2.1. Ray tracing

Fig. 1 shows the four light trapping textures investigated in this paper: (a) the encapsulated-V texture [4] with a V-grooved glass superstrate, (b) the...
embossing process and the light efficiency of our textures shown in Fig. 1. Therefore, we investigate the influence of \( p \) and \( \alpha \) on the maximum short circuit current density, \( j_{sc}^{*} \).

2.2. Experimental

A master stamper is formed from (100)-oriented monocrystalline silicon. We etch periodic inverted pyramids with a facet angle \( \alpha = 54.7^\circ \) and period \( p = 13 \mu m \) into the silicon surface with KOH-etch. The position of the pyramids is defined photolithographically.

Sols are synthesized from tetraethoxysilan (TEOS), trimethoxysilan (MTEOS) and silica sol (Levasil 300/30) using hydrochloric acid as catalyst for hydrolysis and condensation. After stirring the sol for 10 min in an ice bath, sols are filtered with a 0.8 \( \mu m \) cellulose acetate filter. We filter and coat the sol on a clean soda lime glass to obtain the gel film.

We prepare silicon caoutchouc replicas from the master stamper. This material provides adhesion of the stamper to the gel film. The stamper is pressed into the wet gel film with a well defined load. Both, stamper and gel film are dried at 100°C for 1 h, prior to stamp removal. Finally, we densify the patterned coating at 500°C for 1 h. In order to obtain crack free surface relief structures, the temperature for Si deposition should not exceed 500°C because residual CH\(_3\)-groups from the MTEOS would decompose at higher temperatures.

We deposit a microcrystalline (\( \mu c \)) Si layer of thickness \( W = 2.8 \mu m \) by ion assisted Si evaporation [9] at a substrate temperature of 480°C onto the textured sol-gel glass and a non-textured flat glass.

3. Results

3.1. Ray tracing

Fig. 2 shows that \( j_{sc}^{*} \) increases with decreasing \( p \) due to improved randomization of light propagation in structures with more ridges per cell area [5–7]. The current density \( j_{sc}^{*} \) saturates on a high level for \( p < 4 W \) (here: \( p < 16 \mu m \)).

Fig. 3 investigates the dependence of \( j_{sc}^{*} \) for small \( p = 15 \mu m \) on \( \alpha \). Non-textured cells (\( \alpha = 0^\circ \)) of thickness, \( W = 4 \mu m \), yield \( j_{sc}^{*} = 20 \text{ mA/cm}^2 \). At
Fig. 2. All four textures show an increase in maximum short circuit current density \( j_{sc}^* \) with decreasing period \( p \). The statistical error of the numerical \( j_{sc}^* \) data is 0.1 mA/cm\(^2\).

\( \alpha = 75^\circ \), \( j_{sc}^* \) reaches 38 mA/cm\(^2\). All rays of light that leave the cell structure without entering the Si at least once contribute to current loss, \( j_{ref} \). Fig. 3 shows \( j_{ref} \) that decreases with increasing facet angle \( \alpha \).

3.2. Experimental

Fig. 4 shows two scanning electron microscope images of the \( \mu \)-Si layer, the sol–gel glass, and the glass substrate. The patterned coating has a maximum angle \( \alpha = 40^\circ \) instead of \( \alpha = 54.7^\circ \). The measured angles vary between \( \alpha = 40^\circ \) at the ridges and \( \alpha = 0^\circ \) at the bottom of the pyramids. Optical reflectance measurements of the sample shown in Fig. 4 show an optical absorption larger than for a co-deposited flat (\( \alpha = 0^\circ \)) sample.

4. Discussion

4.1. Ray tracing

Our textures fall into two classes in Fig. 2: (i) The three-dimensional textures (3D) with a large \( j_{sc}^* \) at small \( p \) and (ii) the two-dimensional (2D) encapsulated-V texture with a smaller \( j_{sc}^* \). The 3D-textures performs better because the average path length of light is larger. We calculate an average path length \( L = \frac{49 \pm 2.6}{\cos(\alpha)} \) for the 3D textures and \( L = \frac{12 \pm 1.5}{\cos(\alpha)} \) for the encapsulated-V texture. Here, \( W_{eff} = W/\cos(\alpha) \) denotes the effective thickness. These values are close to the theoretical limits \( L_{2D} = 4nW_{eff} \) and \( L_{3D} = 4n^2W_{eff} \), set by the dimensionality of the texture [1] where \( n \) denotes the refractive index of Si at a wavelength of 1000 nm. The limiting value, \( L_{3D} = 4n^2W_{eff} \), is reached for all
p and most \( \alpha \) (checked with 10% accuracy). Hence, the \( p \)-dependence of \( J_{sc} \) shown in Fig. 2 is not caused by a \( p \)-dependent \( L \), but by a \( p \)-dependent standard deviation of the path length distribution, \( p(l) \), as explained in Refs. [6,10].

Fig. 2 shows that texturing almost doubles the current to be expected from the solar cell. There is no detectable difference in performance of the different 3D textures at large \( \alpha \). According to comprehensive transport modeling the efficiency of very thin solar cells is current controlled rather than voltage controlled [11]. Hence, large facet angles are advantageous not only in terms of current but also in terms of cell efficiency.

Fig. 3 shows \( J_{ref} \) to decrease with increasing \( \alpha \), since the rays of light have more attempts to enter the Si film for large \( \alpha \). The current loss \( J_{ref} \) is still 3 mA/cm\(^2\) for very large \( \alpha \), due to the reflectance at the air/glass interface. The importance of this loss mechanism was identified by Scheydecker and his solution was to texture the front side of the glass superstrate [12]. Our calculations demonstrate that for \( W = 4 \) \( \mu \)m thick Si films current densities as high as 40 mA/cm\(^2\) are possible for square pyramidal-film textures (\( \alpha = 75^\circ \), \( p = 15 \) \( \mu \)m) if the front side of the glass is textured with grooves (\( \alpha = 75^\circ \)).

4.2. Experimental

The deviations of the patterned sol–gel glass from the shape of the stamper are caused by shrinkage, which results from a not yet optimized embossing process. Optimization of stamper manufacturing and embossing process are required. The sol–gel process could similarly be applied to the front side of the glass superstrate in order to reduce the reflectance at the air/glass interface.

5. Conclusions

Glass substrates textured by embossed sol–gel glasses present a novel technique to introduce light trapping schemes into thin film solar cells. According to our numerical work sol–gel processes that yield textures with large facet angles \( \alpha \) must be developed.

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References