# Light scattering properties of surface-textured substrates for thin-film solar cells

O. Isabella, K. Jäger, J. Krč., and M. Zeman

*Abstract*—**Optical properties of two different types of surface textures of transparent substrates for thin-film silicon solar cells were investigated: (A) random texture and (B) one-dimensional periodic texture. Asahi U-type and ZnO:Al substrates are analyzed as the representatives of randomly textured substrates and one-dimensional diffraction gratings with different period and height were used as the representatives of periodically textured substrates. The morphology of the textured surfaces was characterized by atomic force microscopy and scanning electron microscopy. Light scattering parameters – haze and angular distribution function of scattered light – of the substrates were determined using total integrated scattering and angular resolved scattering, respectively. Single junction amorphous silicon solar cells were deposited on both random and periodic surface-textured substrates. Solar cells deposited on periodic substrates demonstrate similar performances as the cells on randomly textured substrates.**

*Index Terms*—**thin-film solar cell, light scattering, random texture, one dimensional periodic grating.**

## I. INTRODUCTION

SUSTAINABLE energy generation gained high importance in recent years. Solar cells have become one of the most promising candidates for sustainable electricity production. The challenge of solar cell technologies is to lower the production costs and shorten the energy pay-back. Since thin-film technology promises a low-cost production, the research-focus was shifted from conventional to thin-film solar cells in the last years [1].

One way to improve the efficiency of thin-film solar cells is to increase the absorption in the absorber layers. Therefore the manipulation of light inside the solar cells is an important issue in improving the performance of the cells. Several light management techniques have been investigated intensively, among them the introduction of randomly-textured surfaces to allow light scattering [2], periodically-textured surfaces to enable angle-selective scattering [3] and, recently, photonic crystal structures that are capable of wavelength-selective manipulation of light in the cell [4].

Nowadays in high-quality thin-film silicon technology glass substrates are covered with transparent conductive oxides (TCO's). The surface of the TCO has random surface texture to allow the scattering of light. The most widely used TCO's today are the Asahi U-type ($SnO_2$:F) and ZnO:Al. However, novel types of surface morphologies are of great interest in order to enhance light scattering and increase the photocurrent of the thin-film solar cells. In this respect, periodic gratings are promising candidates since they enable light scattering in large scattering angles. Thus, periodically surface-textured substrates present an interesting alternative to randomly surface-textured substrates due to the easy manipulation of scattering properties by controlling their geometrical features, such as the period, $P$, and the groove height, $h$ [5].

In this contribution the morphology and the optical properties of (A) randomly-textured (Asahi U-type and ZnO:Al) substrates and (B) one-dimensional (1-D) periodic substrates are investigated and compared. Thin-film silicon solar cells deposited on surface-textured substrates are evaluated.

While the surface texture of the Asahi U-type substrate grows during the deposition of the TCO, the texture of the ZnO:Al film is etched chemically after the deposition. In the case of the periodic texture, the grating structures were engraved in glass substrate. Results of morphological and optical characterization of the substrates are presented in this article.

The theories that are nowadays used to link the morphology of such textured surfaces to optical properties, namely the angular distribution function of the transmitted scattered light, $ADF_T(\varphi_{\text{scatt}})$, and the wavelength dependent haze parameter for the transmitted light, $H_T(\lambda)$, are presented and analyzed for the two types of substrates.

Amorphous silicon based solar cells were deposited onto the substrates to investigate the effect of the structures on the spectral and electrical output characteristics. The performance of the solar cells deposited on periodic gratings is comparable to the performance of the cells on the standard Asahi U-type substrate.

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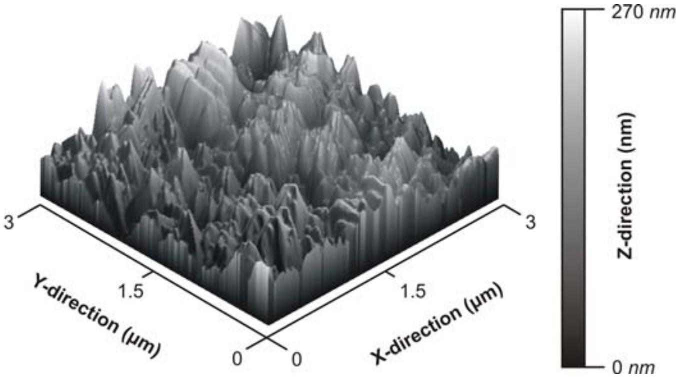

Fig. 1 AFM image of the Asahi U-type sample.

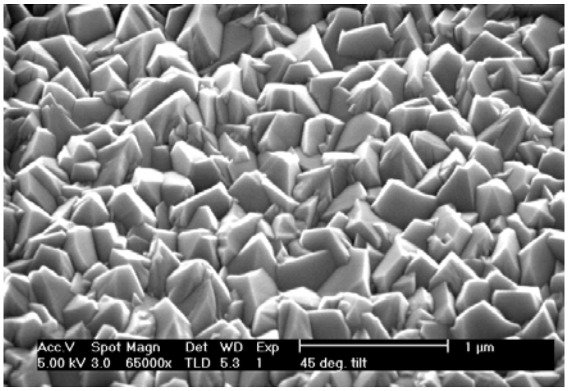

Fig. 2 SEM image of the Asahi U-type sample.

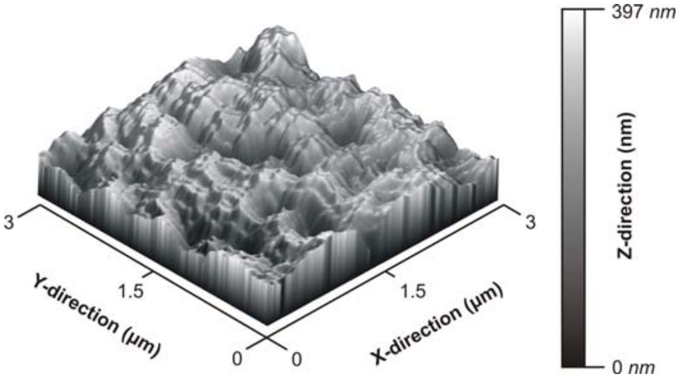

Fig. AFM image of the ZnO:Al (30" etched) sample.

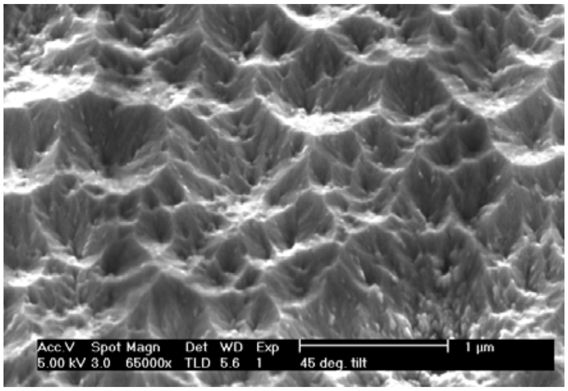

Fig. 4 SEM image of the ZnO:Al (30" etched) sample.

## II. TEXTURED SUBSTRATES

### *A. Randomly-textured substrates*

The Asahi U-type consists of glass coated with a film of $SnO_2$:F. To produce the ZnO:Al TCO, glass was coated with RF magnetron sputtered ZnO:Al. Randomly-textured surfaces on ZnO:Al were created using wet-etching in 0.5% diluted HCl solution. Different textures were obtained by varying the etching time.

The morphological analysis was done using atomic force microscopy (AFM) and scanning electron microscopy (SEM). The surface of the Asahi U-type has a pyramidal structure (see Fig. 1 and Fig. 2), whereas the structure of the etched ZnO:Al TCO is crater-like (see Fig. 3 and Fig. 4).

For the mathematical characterization of the surface texture, the statistical root-mean-square roughness $\sigma_r$ was used. It is defined by

$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(z_i - \hat{z}\right)^2}\ , \tag{1}$$

where $N$ is the number of data points, $\hat{z}$ is the average surface level (zero level) and $z_i$ is the height of the $i$-th data point in an AFM scan. In Fig. 5 the height distribution of the analyzed surfaces are shown as well as the measured $\sigma_r$. One can observe a Gaussian-like height distribution for the Asahi U-type substrate (pyramidal surface, $\sigma_r \approx 40$ nm) which is not the case for the ZnO:Al substrate ($\sigma_r \approx 60$ nm).

### *B. One-dimensional periodic diffraction gratings*

For a better control of light propagation inside thin-film solar cells, the diffraction gratings allow to lower the total reflection in the wavelength region of interest and to scatter light into pre-selected angles by manipulating the period $P$ and groove height $h$ of the grating. Several 1-D rectangular periodic gratings were fabricated, were $P$ was in the range between 400 nm

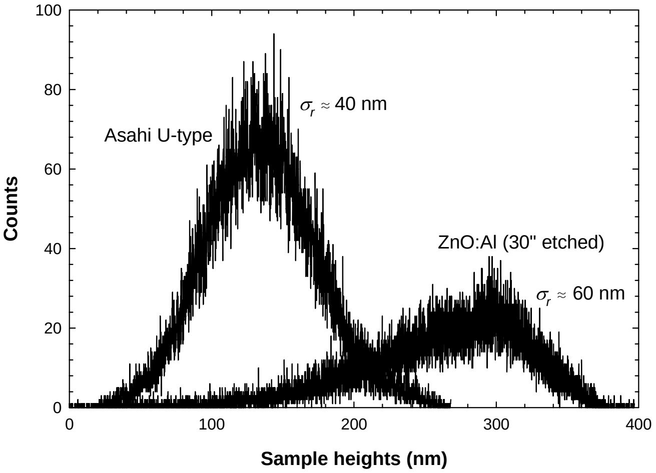

Fig. 5 Surface height distribution for Asahi U-type and ZnO:Al (30" etched) samples.

and 1500 nm and $h$ was between 50 nm and 300 nm. The aspect-ratio (duty cycle, $d_c$) between the length of the upper structure and the period of the grating was designed constant at a value of 50%.

The designed features were inspected with AFM and SEM setups. Fig. 6 and Fig. 7 show the AFM image of a grating with $P$ = 1000 nm and $h$ = 300 nm and its cross section along $x$-direction, respectively. The SEM picture of a grating with $P$ = 1500 nm and $h$ = 250 nm is shown in Fig. 8.

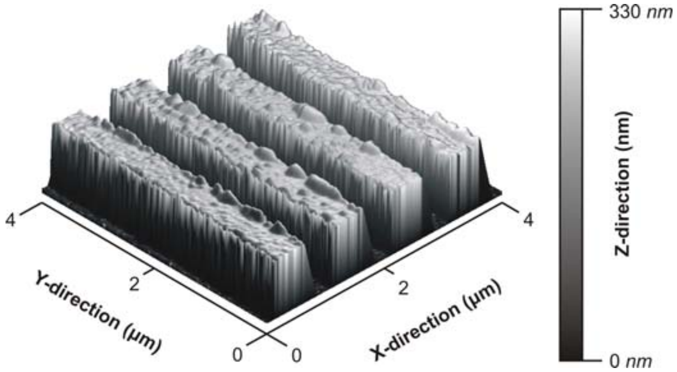

Fig. 6 AFM image of a grating with $P$ = 1000 nm and $h$ = 300 nm.

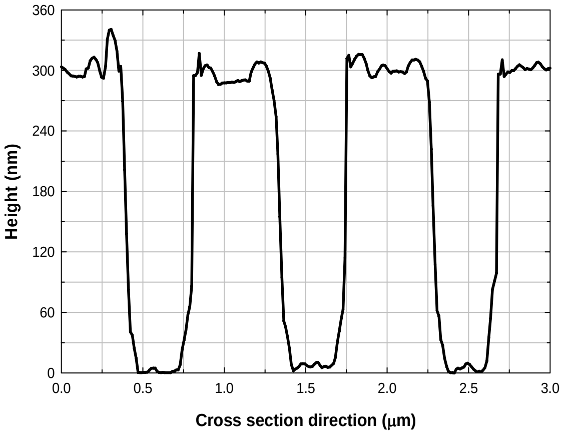

Fig. 7 Cross section of the grating with $P$ = 1000 nm and $h$ = 300 nm along the $x$-direction.

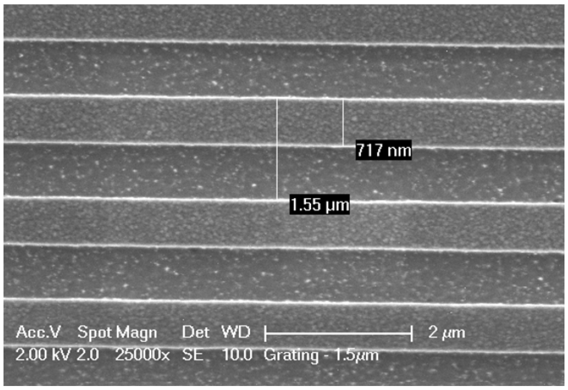

Fig. 8 SEM picture of a grating with $P$ = 1500 nm and $h$ = 250 nm.

### C. *Optical properties of the substrates*

The textured surfaces were optically characterized by measuring the $ADF_T(\varphi_{\text{scatt}})$, the total transmittance, $T_T(\lambda)$, and the diffused transmittance, $T_{diff}(\lambda)$.

The $ADF_T$ was obtained with an angular resolved scattering (ARS) setup that works with a red laser of 633 nm wavelength. To measure $T_T$ and $T_{diff}$, a PerkinElmer Lambda 950 spectrometer equipped with a total integrating sphere was used. The samples were illuminated from the glass side and the mentioned quantities were measured at the textured side.

So far there is no analytical approach available that links the angular distribution function with the surface textures of the substrates. Anyway, recent results show that it is possible to design randomly-textured surfaces having a priori given $ADF_T$ by means of numerical simulations [6].

In Fig. 9, the measured $ADF_T$ is shown for Asahi U-type, ZnO:Al (40” etched, $\sigma_r \approx 110$ nm) and the 1-D diffraction grating with $P$ = 700 nm and $h$ = 80 nm.

Whereas the $ADF_T$ of the Asahi U-type can be linearly interpolated in Cartesian plot, the $ADF_T$ of etched zinc-oxide appears as an ellipse when parameterized in polar plot. It can be parameterized as

$$r(\varphi) = K \frac{2ab^2}{\cos\varphi(b^2 + a^2 tg^2\varphi)}, \qquad (2)$$

where the radii ($a$ and $b$) and the angle $\varphi$ depend on interface roughness, angle of specular beam and wavelength [7]. The factor $K$ is a normalizing constant. Although the parameters have to be found empirically, the elliptical parameterization allows an easy description of the $ADF_T$ (see Fig. 10).

The presence of scattering modes in the $ADF_T$ of 1-D periodic gratings can be observed in Fig. 9, because these sub-

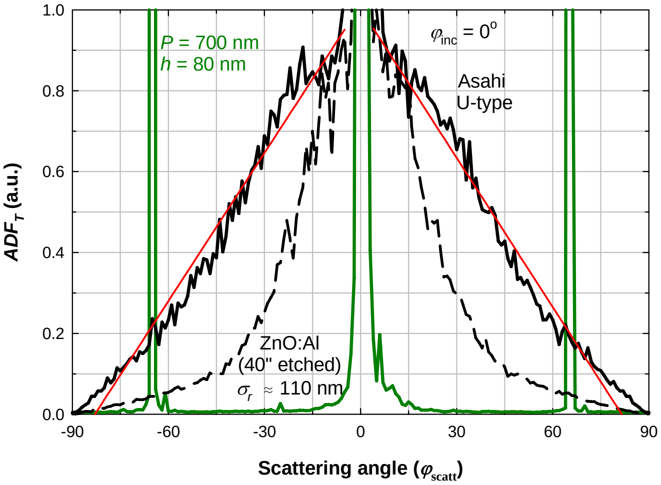

Fig. 9 ADF$_T$ of Asahi U-type (black continuous line), ZnO:Al (40” etched) (black dashed line) and grating ($P$ = 700 nm and $h$ = 80 nm) (green line). Red continuous lines are linear interpolations of the Asahi’s trend. Measurements are performed for an incident angle $\varphi_{\text{inc}}$ = 0 deg at the wavelength $\lambda$ = 633 nm, air surrounding.

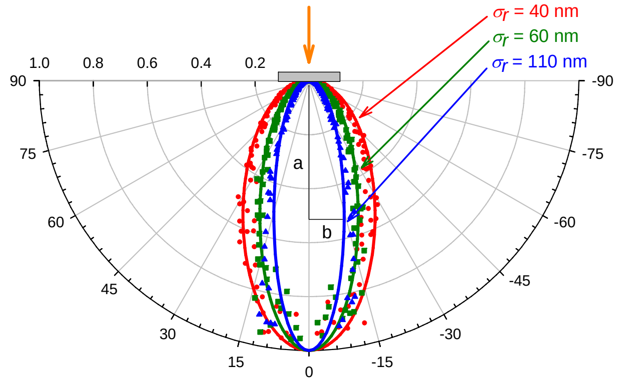

Fig. 10 $ADF_T$ (polar plot) of differently etched ZnO:Al substrates (measured points - dots, descriptive ellipses - lines).

strates support scattering into the distinct angles only as predicted by the diffraction grating equation [7]

$$\varphi_{scatt} = \arcsin\left[\frac{m\lambda}{nP} - \sin(\varphi_{inc})\right]. \quad (3)$$

The total transmittance of the randomly-textured substrates is shown in Fig. 11. The typical onset of ZnO:Al with respect to $SnO_2$:F is present due to different short-wavelength absorption of the two TCO materials. Interference fringes are observed for the Asahi U-type substrate, since more coherent (non-scattered) light is present in the glass/TCO optical system due to lower roughness, compared to the ZnO:Al sample.

In Fig. 12 the total transmittance of 1-D periodic gratings with different periods ($P$ = 500, 600, 750, 1000 nm) and constant height ($h$ = 300 nm) is reported. The trends reveal absorption features in wavelength ranges close to the period of the gratings.

The absolute scattering level of transmitted light from a textured interface is described by the haze parameter for transmittance, $H_T(\lambda)$, which is the ratio between the total and the diffused transmittance (see Fig. 13 ).

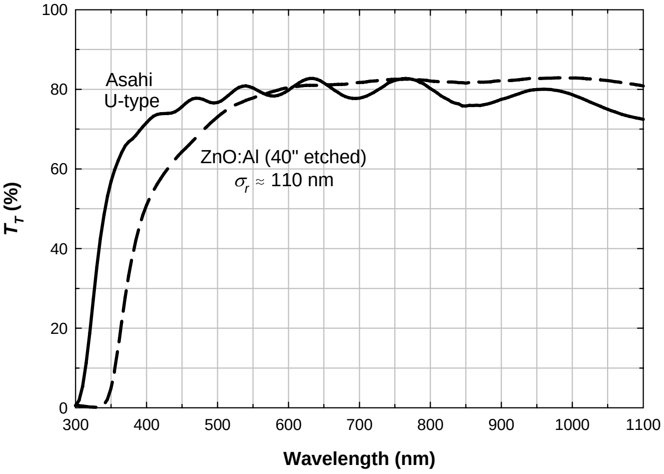

Fig. 11 Total transmittance of Asahi U-type (continuous line) and ZnO:Al (40" etched) (dashed line) substrates measured in air surrounding.

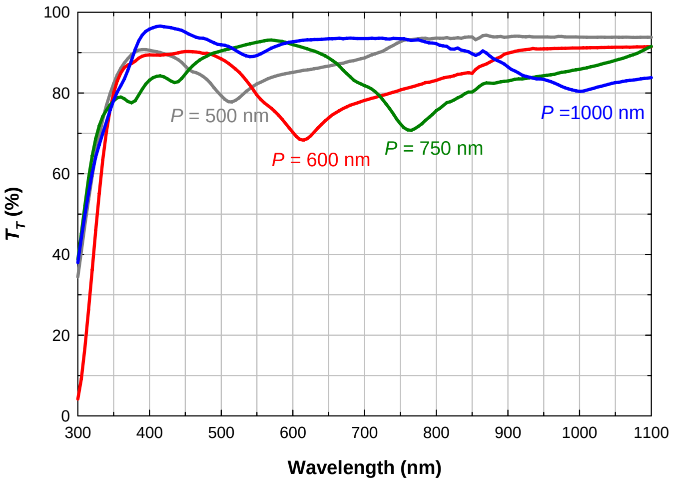

Fig. 12 Total transmittance of the substrates with gratings with $P$ = 500, 600, 750 and 1000 nm with constant height ($h$ = 300 nm) as measured in air surrounding.

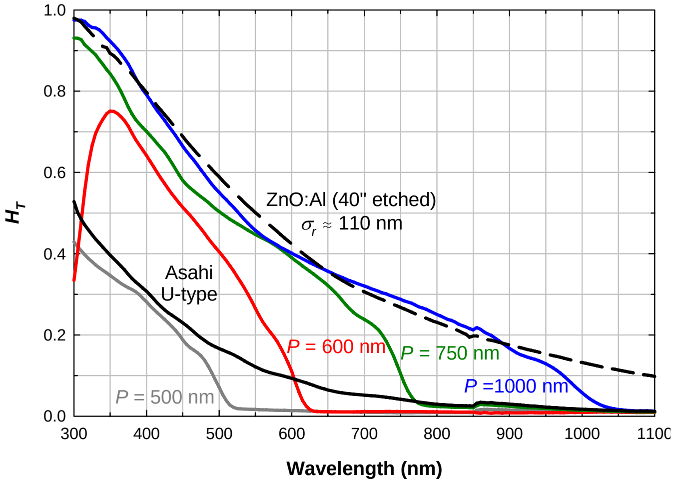

Fig. 13 Haze parameter in transmission of Asahi U-type (black continuous line), ZnO:Al (40”etched) (black dashed line) and gratings with $P$ = 500, 600, 750 and 1000 nm with constant height ($h$ = 300 nm) (colored lines) measured in air surrounding.

The link between the morphology and the haze parameter for transmittance is an involved task. One way to describe the exponential decay of $H_T$ for randomly-textured substrates was proposed in [7]:

$$H_T(\lambda) = 1 - \exp\left[-\left(\frac{4\pi\sigma_r c_T \left|n_1\cos\varphi_{inc} - n_2\cos\varphi_{out}\right|}{\lambda}\right)^a\right], \quad (4)$$

where $\sigma_r$ is the root-mean-square roughness (see above), $n_1$ and $n_2$ are the real parts of complex refractive indices of the layers forming the interface, $\varphi_{inc}$ is the incident and $\varphi_{out}$ is the outgoing angle of the specular beam. The correction function $c_T$, which is dependent on wavelength and root-mean-square roughness, as well as the factor $a$ ($a$ = 2-3) were introduced as empirical parameters to match the experimental to the simulated data. Equation (4) is based on the scalar scattering theory [8] that relates the surface structure to the haze parameter with a statistical approach. It is suitable for surfaces whose root-mean-square roughness is smaller than the wavelength and whose height distribution follows a Gaussian shape.

### *D. Discussion*

From the optical analysis of randomly-textured substrates, the ZnO:Al (40” etched) presents a higher scattering level than the Asahi U-type, due to much higher roughness of the zinc-oxide. In both case there is a general agreement between measured trends and equation (4).

The optical analysis of the 1-D periodic gratings revealed that for $\lambda$ (in air) < $P$ a pronounced scattering in transmission is detected at the gratings that decreases with the increasing $\lambda$ and disappears for $\lambda > P$. The desired scattering behaviour can be manipulated for a chosen wavelength by designing an appropriate period of the grating. Also the height of the gratings plays an important role: by changing its value the amount of scattering can be opportunely tuned [5].

## III. SOLAR CELLS ON TEXTURED SUBSTRATES

### *A. Structure of the solar cells*

Thin-film silicon solar cells were deposited using RF PE-CVD deposition technique in p-i-n configuration on the investigated substrates. The solar cells have the following structure: glass / TCO / p-layer (microcrystalline µc-Si:H) / p-layer (a-SiC:H) / buffer layer (a-SiC:H) / i-layer (300 nm a-Si:H) / n-layer (a-Si:H) / Ag / Al. The light is entering the solar cell structure from the glass side (superstrate configuration).

To prevent the $SnO_2$:F from reduction during the deposition of the microcrystalline p-layer, an additional thin layer of ZnO:Al was deposited on top of the Asahi U-type substrate (see Fig. 14 for the complete solar cell). In the case of ZnO:Al based substrates the random textures were created by wet-etching the surface for 40” seconds (see Fig. 14 for the complete solar cell). In the case of periodically textured substrates the ZnO:Al TCO was deposited using RF magnetron sputtering on glass engraved with a 1-D periodic grating ($P$ = 600 nm and $h$ = 300 nm) (see Fig. 15 for the complete solar cell). The deposition conditions of the cell on the grating have not been fully optimized yet and the same deposition conditions were used as in the case of cells on randomly textured substrates.

### *B. Results*

The performance of the cells was tested under standard condition (AM1.5, 25 ºC, 1000 $Wm^{-2}$). The current-voltage *(J-V)* characteristics are presented in Fig. 16.

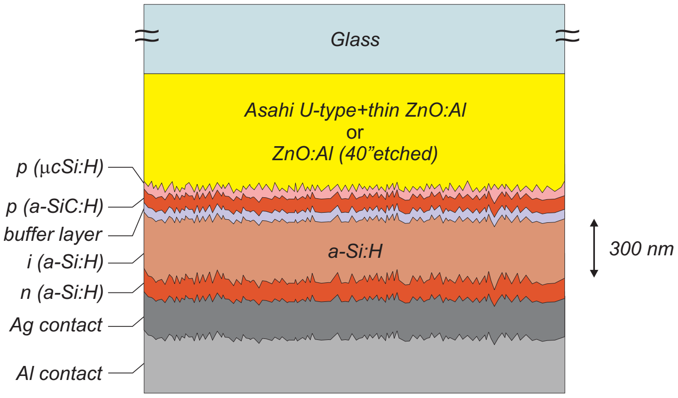

Fig. 14 Thin-film silicon solar cell structure on Asahi U-type or ZnO:Al (40” etched) front TCO substrate.

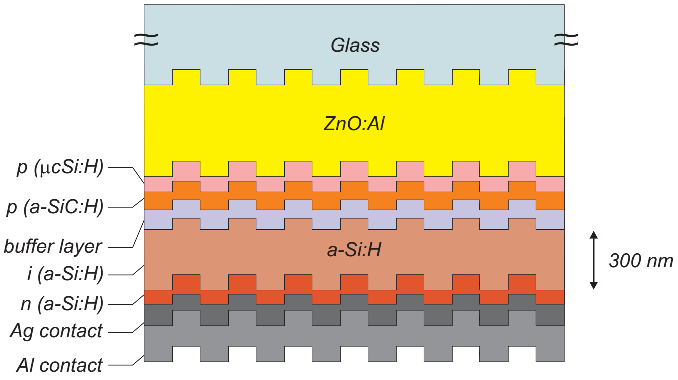

Fig. 15 Thin-film silicon solar cell structure on grating with ZnO:Al front TCO substrate.

The wavelength-dependent external quantum efficiency (*EQE*) was measured in the range between 300 nm and 800 nm (see Fig. 17). For wavelengths above 500 nm, the solar cell fabricated on gratings demonstrate similar *EQE* as the solar cell deposited on Asahi U-type (indicating good but not yet optimized scattering and anti-reflecting properties). On the other hand, for wavelengths below 500 nm, one can observe a decrease in the *EQE* for both cells with ZnO:Al substrate due to the absorption losses in ZnO:Al front contract (see also Fig. 10). However, the losses are smaller for the cell on the grating (possibly due to more pronounced anti-reflecting effect).

The short circuit current density, $J_{sc}$, the open circuit voltage, $V_{oc}$, the fill factor, $FF$, and the efficiency, $\eta$ of the cells,

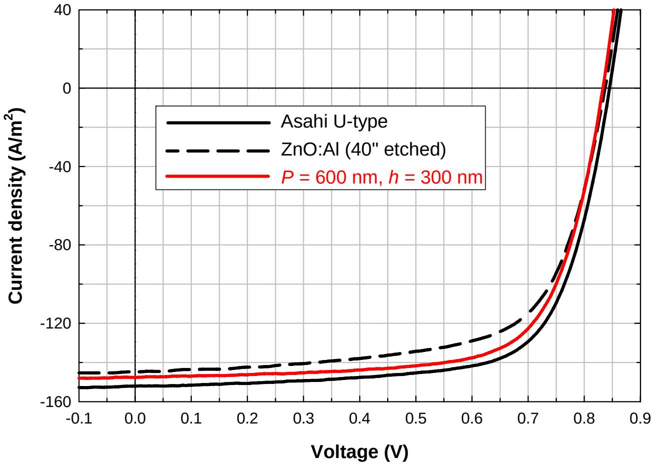

Fig. 16 *J-V* characteristics of the cells on Asahi U-type, ZnO:Al (40” etched) and grating ($P$ = 600 nm and $h$ = 300 nm) (red line) substrate.

are summarized in table I. The last row corresponds to the grating with $P$ = 600 nm and $h$ = 300 nm. Particularly, the $FF$ and the $V_{oc}$ of the cell deposited on the grating have values comparable with the randomly-textured substrates (indicating good electrical properties).

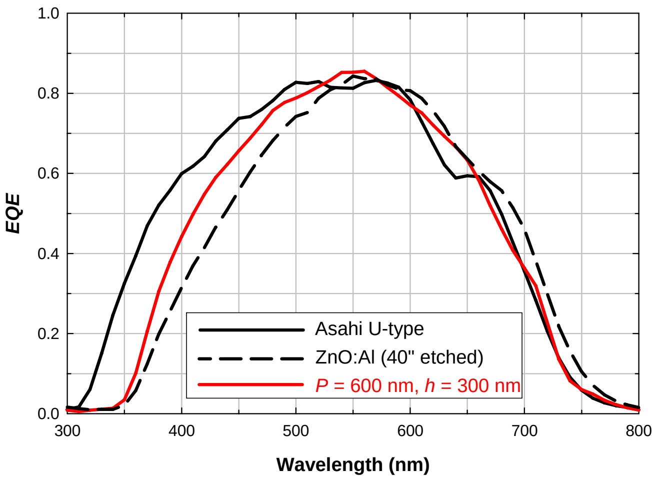

Fig. 17 *EQE* of the cells on Asahi U-type, ZnO:Al (40” etched) and grating ($P$ = 600 nm and $h$ = 300 nm) substrate.

TABLE I

SOLAR CELLS EXTERNAL PARAMETERS

| Texture | $V_{oc}$ [V] | $J_{sc}$ [Am$^{-2}$] | *FF* | $\eta$ [%] |
|---|---|---|---|---|
| Asahi-U | 0.845 | - 152 | 0.708 | 9.00 |
| ZnO:Al | 0.837 | - 145 | 0.672 | 8.14 |
| 600x300 | 0.833 | - 148 | 0.707 | 8.70 |

## IV. CONCLUSION

Randomly-textured and 1-D periodically-textured substrates were compared with each other and used as substrates for thin-film silicon solar cells.

Morphological and optical analysis demonstrated the possibility to manipulate the light scattering by changing parameters such as surface roughness in randomly-textured surfaces and period and height in 1-D periodic gratings. However, the link between the surface morphology and the optical parameters is not fully established.

Thin-film silicon based solar cells were deposited on investigated surface-textured substrates. The electrical and spectral performance of cells on the 1-D periodic gratings with ZnO TCO is comparable to the performance of cells deposited on randomly-textured TCO’s. This indicates that periodically-textured substrates have a real potential for becoming suitable substrates for high efficient thin-film silicon solar cells.

## ACKNOWLEDGMENT

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