

Aluminium induced texturing of glass substrates with improved light management for thin film solar cells

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Abstract

Aluminium induced texturing (AIT) method has been used to texture glass substrates to enhance photon absorption in microcrystalline thin film Si solar cells. In this process, a thin Al film is deposited on a glass substrate and a non-uniform redox reaction between the glass and the Al film occurs when they are annealed at high temperature. After etching the reaction products, the resultant glass surface presents a uniform and rough morphology. In this work, three different textures ($\sigma_{\text{rms}} \sim 85, \sim 95, \sim 125$ nm) have been achieved by tuning the dc sputtering power and over them and over smooth glass, *pin* microcrystalline silicon solar cells have been fabricated. The cells deposited over the textured substrates showed an efficiency improvement in comparison to the cells deposited over the smooth glass. The best result was given for the glass texture $\sigma_{\text{rms}} \sim 125$ nm that led to an average efficiency 2.1% higher than that given by the cell deposited on smooth glass.

1. Introduction

For thin film silicon solar cells efficient light management plays a crucial role to improve device performance [1]. A common approach to improve light management involves introduction of textured interfaces in the solar cell. Scattering at the interfaces increases the path length of incident light aiming in higher absorption in the active layer and hence, higher conversion efficiency.

In thin film silicon solar cells, light scattering is usually achieved by texturing the front transparent conducting oxide (TCO) [2, 3, 4], the back reflector [5], or even the substrate with either random [6, 7] or periodic [8, 9] textures with typical roughness in the range between 30 to 150 nm [1–8]. For efficient light scattering, these textures should be in the dimension range of the incoming light wavelength [10].

Typical textured TCOs are the naturally textured ZnO:B grown by Low Pressure Chemical Vapour Deposition (LPCVD) [2], SnO₂:F grown by Atmospheric Pressure Chemical Vapour Deposition (APCVD) [3], or sputtered and HCl-etched ZnO:Al (AZO) [5]. Besides these “traditional” light trapping schemes, other nanoscale approaches are currently under investigation including photonic crystals [11], nanowires [12], and periodic or periodic-disordered nanostructures [13].

Texturing the substrate is a good alternative compared to texturing the TCO or the back reflector. An optimized textured glass surface will provide a wider range of TCOs which are suitable for thin film solar cells, for example non-texturable TCOs or alternative front contacts, such as carbon nanotubes [14]. Moreover texturing the glass gives the possibility for two fold light scattering at two interfaces (glass/TCO and TCO/silicon) as exhibited in Fig. 1.

In this work the Aluminium Induced Texturing method (AIT) has been used to texture Borofloat glass substrates. In this method, a thin Al film is deposited onto a glass substrate and a redox reaction between the Al and the SiO₂ of the glass is induced by high temperature annealing. The reaction products are wet-etched and the result is a uniform and rough glass surface [15]. The final roughness can be controlled by varying the process parameters such as the etching solution [16, 17], the etching time [18], the initial Al thickness [6], the annealing conditions [18] or the Al deposition method [6]. The AIT method can create suitable substrate textures for polysilicon solar cells [16–19] as well as for amorphous and microcrystalline thin film silicon solar cells [18].

In this study, the glass roughness has been controlled by varying the dc sputtering power to deposit the Al, and textures with roughness values of ~85 nm (sample T1), ~95 nm (sample T2) and ~125 nm (sample T3) have been obtained. Over these textures and over smooth glass, an AZO film of 800 nm has been deposited followed by identical μ c-Si:H *pin* solar cells. *J-V* measurements have confirmed the suitability of

these textures for the growth of $\mu\text{c-Si:H}$ and have shown an increase in the short circuit current that results in an overall efficiency improvement in comparison to the solar cell on flat substrate.

2. Experimental

Three Borofloat 33 glass substrates of 2 mm thick were cleaned in an ISO 7 (10000 type) clean room. Al films of 180 nm were deposited by means of direct current (dc) magnetron sputtering at 60 W (sample T1), 100 W (sample T2) and 150 W (sample T3) over the three cleaned substrates. The Al target was 99.999% pure and had a diameter of 3 inch. The samples were post-annealed at 600°C during 1h to induce the chemical reaction between the glass surface and the Al layer and the reaction products were etched with H_3PO_4 at 185°C.

Over the resultant textured substrates (T1, T2 and T3) and over the non-textured Borofloat glass (referred to as T0), 800 nm of AZO (ZnO with 2 wt% Al_2O_3 and 99.99% pure) were deposited by dc magnetron sputtering at a substrate temperature of 300°C, using a power density of 220 W and at an Ar pressure of 0.4 Pa.

The morphological study was carried out using a Scanning Electron Microscope (SEM) and an Atomic Force Microscope (AFM). SEM micrographs were obtained through a *Nova Nano SEM 230* from *FEI Electron Microscope*. Insulating samples had to be covered with thin Au layers to avoid the charging of the surface. AFM images were recorded using a *Pacific Instruments* system and the software used for the image analysis was *XEI 1.7.3 of Psia Inc.* and the σ_{rms} values were extracted from areas of $15 \times 15 \mu\text{m}^2$.

The total transmittance (T) and diffused transmittance (T_d) measurements in the wavelength range 350-1400 nm were recorded using a *PerkinElmer Lambda 950* spectrophotometer equipped with a 150 mm integrating sphere. The haze values were calculated from the quotient between the T_d and T according to:

$$\text{Haze} = T_d/T \quad (1)$$

The sheet resistance (R_s) of glass/AZO samples was measured by using a four point probe system (*Jandel RM3*).

Thin film silicon solar cells were deposited on the AZO coated textured glasses and smooth Borofloat glass substrates in the sequence: glass/AZO/ $\mu\text{c-Si:H}$ (p)/ $\mu\text{c-Si:H}$ (i)/

$\mu\text{c-SiOx:H}$ (n). The cells were covered with radio frequency magnetron sputtered ZnO:Al layer and Ag contact deposited with 1 cm^2 mask to define the cell area. Twelve such identical solar cells were fabricated on each of the substrates tested. The schematic cross section of a solar cell is shown in Fig. 1. The thicknesses of the intrinsic and the doped silicon layers are 1100 ± 25 and 20 ± 5 nm, respectively. Additional details on the deposition process can be found elsewhere [20].

Solar cells were characterised by current–voltage (J – V) measurements under AM1.5 illumination using a double source (class A) sun simulator, and by external quantum efficiency (EQE) measurements. The total optical reflection of the cells was measured using a *PerkinElmer Lambda 950* spectrophotometer within a spectral range from 300 to 1300 nm. Although various cells were fabricated on every substrate, the total reflectance, the EQE, and the J - V curves shown in this work belong to the best solar cell (highest efficiency) in each one. The average values of the solar cell parameters shown in Table II were calculated from all the cells except for those presenting short circuit problems which were 1 or 2 per substrate).

3. Results and discussion

The morphology of T1, T2, T3 and AZO coated samples, T1/AZO, T2/AZO and T3/AZO is studied using SEM and the images recorded at a tilt angle of 60° is presented in Fig. 2.

By increasing the dc sputtering power, the Al particles reach the glass with higher energy and the Al film grows more compact and with greater adhesion to the glass substrate. As a result, the glass surface gets more textured. At dc sputtering powers <100 W, the glass surface presents a U-shape crater morphology (see Fig. 2 a) and c)) with lateral feature sizes of 500–900 nm. When the sputtering is performed at 150 W (see Fig. 2 e)) the glass surface becomes highly rough with deeper valleys and smaller lateral sizes. Probably at such high power, the Al atoms have diffused deeper into the glass surface and after completing the AIT process, the result is this highly porous-like structure.

After depositing 800 nm of AZO, the three surfaces present a double texture morphology based on a superposition of a micro- and nano-metric roughness similar to a “cauliflower” surface.

The roughness values can be found in Table I and the haze curves in the range 350–1400 nm are presented in Fig. 3. In accordance with the SEM images, both roughness values and haze factor of the textured glasses are found to increase with the sputtering power. When the textured glasses are coated with the AZO, the roughness and haze values are almost unchanged. Only the highest texture, T3, seems to be slightly smoothed which is beneficial to avoid the formation of cracks during the $\mu\text{-Si:H}$ growth.

A summary with the roughness, sheet resistance, haze value at 600 nm and integrated transmittance in the range 400–1100 nm of all the samples is shown in Table I. The sheet resistance of the AZO on smooth glass is 9 Ω/sq and increases up to $\sim 10 \Omega/\text{sq}$ over T1 and up to $\sim 12 \Omega/\text{sq}$ over T2 and T3.

Identical *pin* $\mu\text{-Si:H}$ solar cells have been fabricated over AZO coated T0, T1, T2 and T3 substrates followed by the back reflector (TCO+Ag) and the total reflectance of the devices in the range 300–1100 nm is exhibited in Fig. 4.

As can be seen from Fig. 4, the solar cells deposited on the textured substrates show a total reflectance significantly lower than that obtained in the case of smooth glass, whose average value is $R_{400-1100}=45.4\%$. The roughness increase at the interface AZO/ $\mu\text{-Si:H}$ leads to an improved optical coupling because the refractive index varies progressively from the glass to the silicon layer, and then, the reflected light component is decreased. As higher is the surface roughness, better is the optical coupling and lower are the optical reflection losses, which suggests that texture T3/AZO in this study is the most appropriate for the fabrication of the cells, presenting an integrated reflectance of $R_{400-1100} = 19.1\%$ and showing the lowest reflection in the short wavelength range.

The fact that the glass surface of sample T3 has smaller lateral sizes than T1 and T2 could be the reason of the lower reflection at short wavelengths as it is known that smaller feature sizes are more appropriate in scattering shorter wavelengths [1].

The surface reflectance of the solar cell has a direct influence on the EQE of the devices. As observed in Fig. 5, the EQE curve of the device on the smooth substrate presents the typical maximum and minimum fringes produced by the optical interferences between the incoming and reflected light at the interfaces glass/AZO and AZO/Si [21]. Thanks to the textured interfaces, the curve becomes smoother throughout the whole spectral range as already seen in related studies [1, 8, 22]. It is observed that substrate texturing significantly improves the long wavelength response (500–1100 nm) for all textures. In contrast, for shorter wavelengths ($\lambda < 600$ nm), only the EQE of the cell on T3/AZO shows slightly greater values than that over T0/AZO, in agreement with reduced cell reflectance in the given spectral range (see Fig. 4).

Comparing the total reflection and the EQE curves, it is observed that the light trapping at long wavelengths does not depend on the degree of glass roughness. On the other hand, in the short wavelength region, small variations in the glass texture are directly affecting the EQE as well as the total reflectance of the devices. As mentioned above, the sample with the smallest lateral features is scattering more efficiently the light at short wavelengths, as a result the light trapping effect is increased.

Additionally, slight variations in the p-type layer thickness could contribute to the differences in short wavelength EQE observed in Fig. 4.

The overall J - V characteristics of the best solar cells (those showing the highest efficiency values) are shown in Fig. 6, and Table II presents the best cell parameters as well as the average parameters of the solar cells on the four different substrates. The photovoltaic performance of the fabricated solar cells suggests that, the three different textures applied here have no deteriorating influence on the growth of silicon layers. The main parameter that is influenced by the substrate morphology is the short circuit current density. Considering the best cells, it is observed that the solar cells deposited over T1/AZO show an increase of $\Delta J_{SC} = 4.9$ mA/cm² compared to the ones deposited over T0/AZO. In the case of T2/AZO, this increase is found to be much higher, with $\Delta J_{SC} = 5.5$ mA/cm² and for the highest texture T3, the short circuit current density increase is $\Delta J_{SC} = 6.7$ mA/cm². The increase in J_{SC} goes along with an increased efficiency of the devices, as fill factor (FF) and open-circuit voltage (V_{OC}) are only slightly affected. The average efficiency improved from 5% to 6.5% in the case of texture T1 and to 6.8% and 7.1% for textures T2 and T3, respectively. As a general

tendency, as higher is the substrate roughness, higher is the current and greater is the solar cell performance. However, it can be observed that the best cell on texture T3 possess a higher J_{sc} but the efficiency is slightly lower than for texture T2, because of the lower V_{OC} and FF . This decrease in V_{oc} and FF values can be attributed to a lower carrier lifetime due to recombination at the p/i and i/n interfaces, as a consequence of the higher roughness. The V_{OC} and FF of the samples with lower roughness (T0-T2) are very similar pointing to similar carrier recombination lifetimes. Probably the recombination lifetime for these samples is dominated by the bulk recombination.

AZO grown on AIT glasses is a good alternative to the commonly used HCl etched AZO or LPCVD ZnO:B. Microcrystalline silicon thin film solar cells grown on AZO-covered AIT substrates have shown similar enhancement in the current density values than that given by $\mu\text{-Si:H}$ grown on sputtered and etched AZO [20]. In the case of cells grown on pyramidal LPCVD ZnO:B, the improvement of the solar cell parameters has been reported to be higher [23]. However, to achieve a uniform and soft pyramid morphology adequate for the growth of microcrystalline silicon, needs a complex optimization and often, post-deposition treatments such as Ar plasma etching are also required [2, 23].

4. Conclusions

The AIT method has been used to create different types of textures on Borofloat glass substrates. The textures were achieved by sputtering the Al at 60, 100 and 150 W, followed by the AIT process, which yielded roughness of ~ 85 nm (texture T1), ~ 95 nm (texture T2) and ~ 125 nm (texture T3), respectively. Over these textures and over smooth Borofloat glass, 800 nm of AZO was deposited by means of dc magnetron sputtering and for the three textures, the resultant surfaces exhibit a double texture morphology (the superposition of a micro and a nanotexture) without deep valleys or sharp edges that may negatively influence the performance of the cells. The haze values at 600 nm were 15% for T1/AZO, 23.7% for T2/AZO and 29.5% for T3/AZO and the sheet resistances were lower than $12 \Omega/\text{sq}$.

Subsequently $\mu\text{-Si:H}$ solar cells of 1 cm^2 were deposited over T1/AZO, T2/AZO, T3/AZO and over AZO coated smooth glass. The electrical characterization of the cells

demonstrate that the AIT method is able to perform suitable textures for $\mu\text{-Si:H}$ solar cells, the cells grew without shunting and in every case gave increased short circuit current values compared to the cells grown on smooth substrates. The integrated reflectance in the range 400-1100 nm of the whole devices had lower values in comparison to the smooth glass and the EQE was smoothed and highly improved at longer wavelengths (500-1100 nm). Considering the average solar cell parameters, when higher was the substrate roughness, higher was the current and greater was the efficiency, in the case of texture T3 (~125 nm), the average cell efficiency was improved by 2.1% relative to the solar cells on smooth substrate.

Acknowledgements

This work has been supported by the Ministerio de Economía y Competitividad and the European Regional Development Fund through the projects INNDISOL (IPT-420000-2010-6) and HELLO (ENE2013-48629-C4-2-R).

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List of Tables

Table I. Roughness (σ_{rms}), sheet resistance (R_s), haze at 600 nm and integrated transmittance (T) in the range 400–1100 nm of T0/AZO, T1, T2, T3, T1/AZO, T2/AZO and T3/AZO.

Sample	σ_{rms} (nm)	Haze (%) (600 nm)	Integrated T (%) (400–1100 nm)	R_s (Ω /sq)
T0/AZO	---	---	79.2	9
T1	80–90	15.0	92.6	---
T1/AZO	80–90	15.0	80.8	10
T2	90–100	21.2	93.7	---
T2/AZO	90–100	23.7	77.6	10–12
T3	120–130	31.0	89.9	---
T3/AZO	90–100	29.5	74.5	10–12

Table II: Average and best values (highest efficiency) of solar cell parameters under AM1.5G illumination for the cells (1 cm^2) on different substrates.

Sample	Eff (%)		FF (%)		V_{OC} (mV)		J_{sc} (mA/cm^2)		R_s ($\Omega \cdot \text{cm}^2$)		R_{sh} ($\Omega \cdot \text{cm}^2$)	
	Best	Av.	Best	Av.	Best	Av.	Best	Av.	Best	Av.	Best	Av.
T0	5.2	5.0	69.6	69.8	521	522	14.3	13.6	4.08	4.67	992	1076
T1	6.8	6.5	68.8	68.9	522	519	18.9	18.3	3.41	4.27	696	1505
T2	7.4	6.8	71.2	69.5	525	523	19.8	18.7	5.11	372	1655	960
T3	7.2	7.1	66.5	67.2	519	520	21.0	20.4	3.67	3.99	727	845

Figure captions

Figure 1. Schematic light path of a *pin* thin film silicon solar cell deposited on a textured glass surface.

Figure 2. SEM images recorded at a tilt angle of 60° of the textured glass substrates achieved by sputtering the Al at different powers and the resultant surface morphology after depositing 800 nm of AZO. a) Texture T1, 60 W, b) Texture T1/AZO, c) Texture T2, 100 W, d) Texture T2/AZO, e) Texture T3, 150 W, and f) Texture T3/AZO.

Figure 3. Haze for samples T1, T2 and T3, T1/AZO, T2/AZO and T3/AZO in the range 350–1400 nm.

Figure 4. Reflectance curves of the best solar cells deposited on T0, T1, T2 and T3 and integrated reflectance values in the range 400–1100 nm.

Figure 5. Comparison between the quantum efficiency curves obtained for the best solar cells on each of the substrates tested.

Figure 6: *J-V* curves under AM1.5G illumination for the best solar cells deposited on the different substrates.

Figure 1

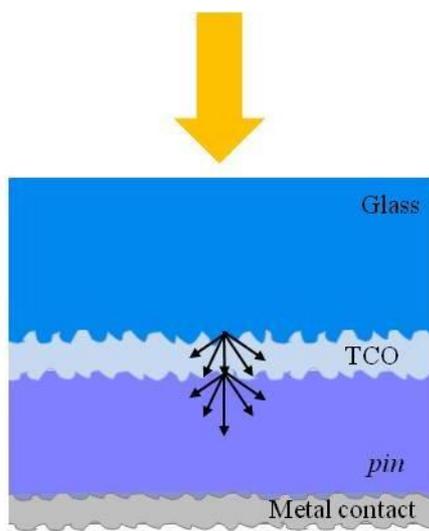


Figure 2

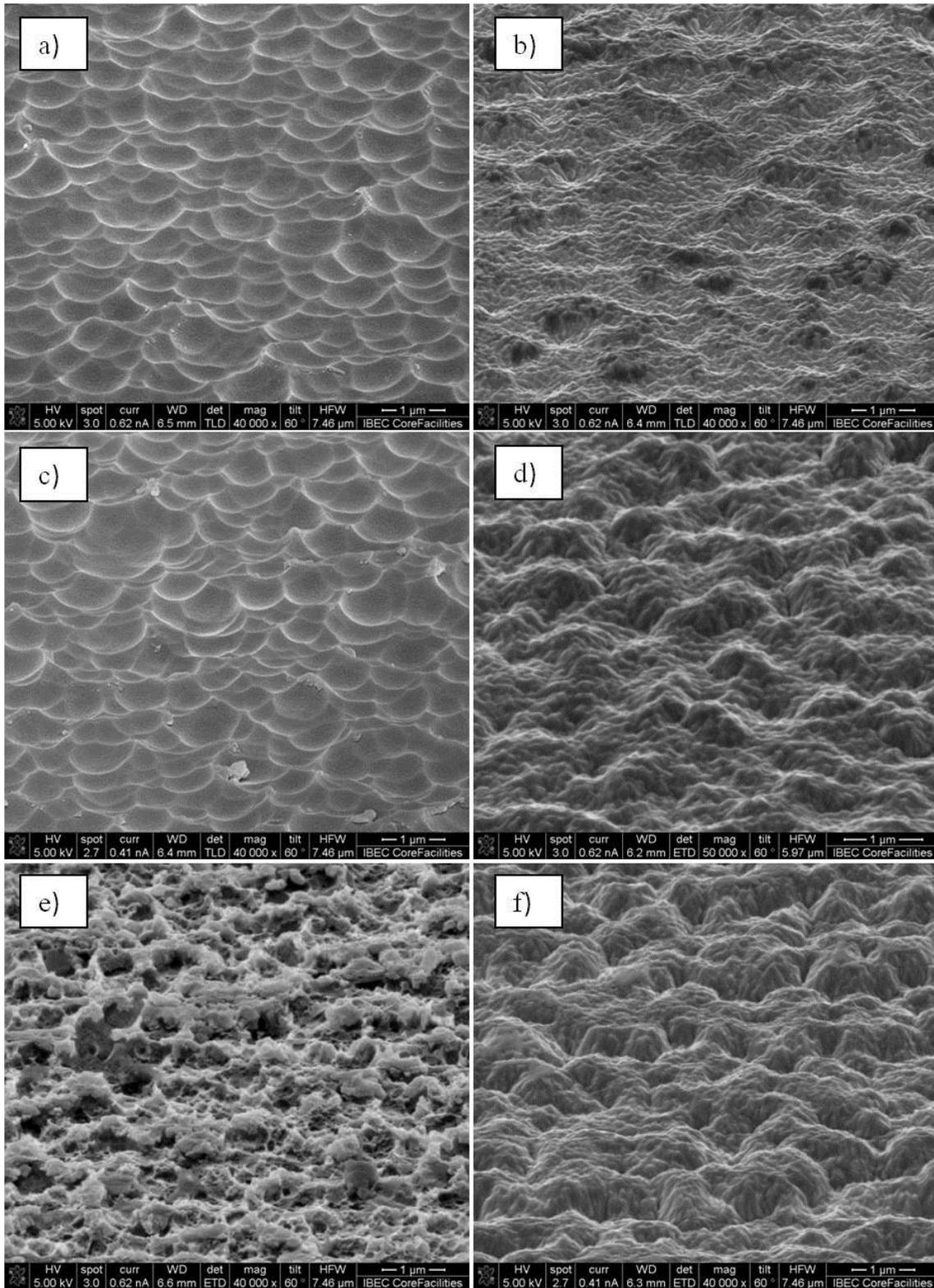


Figure 3

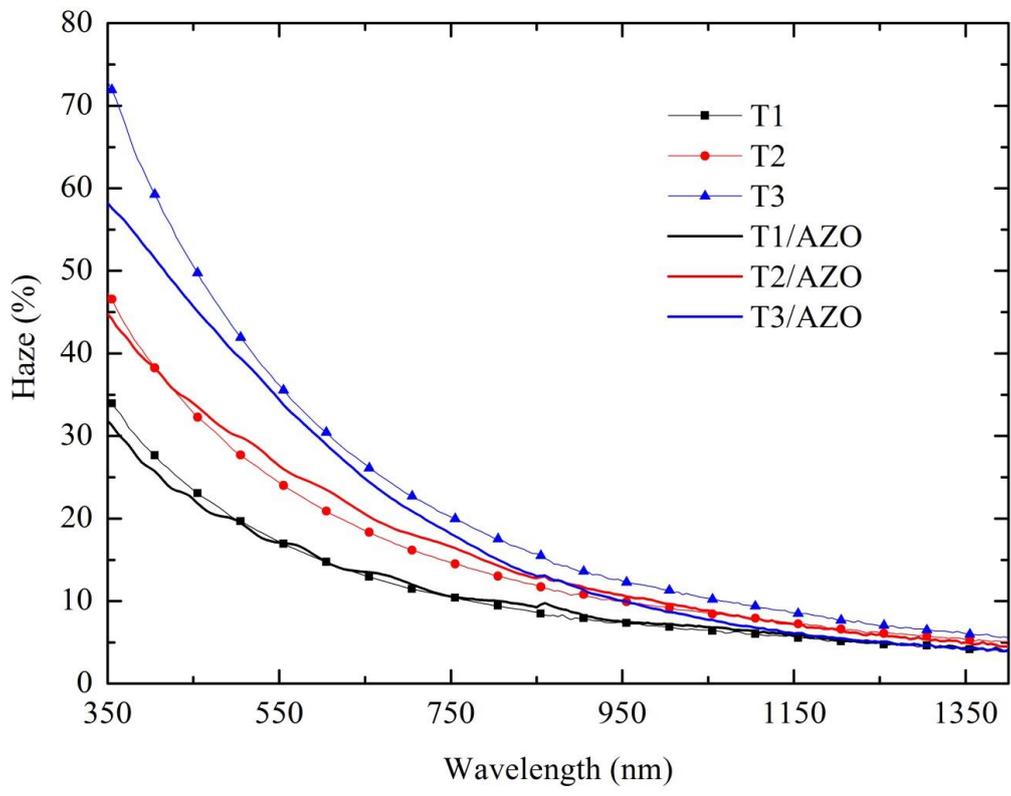


Figure 4

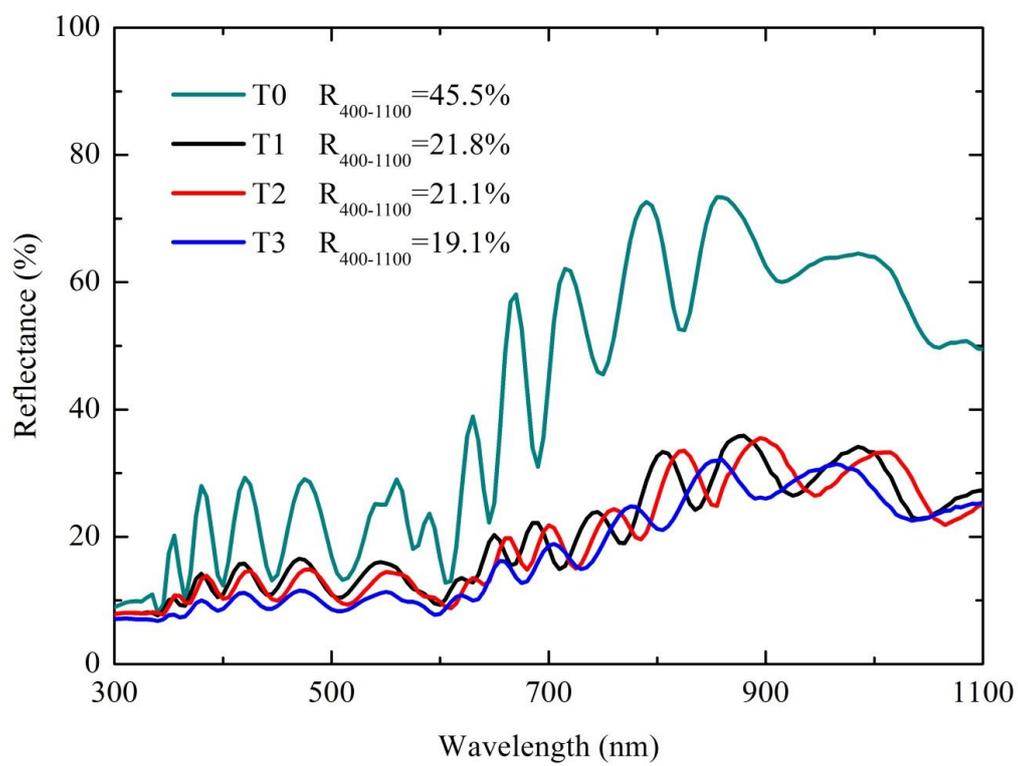


Figure 5

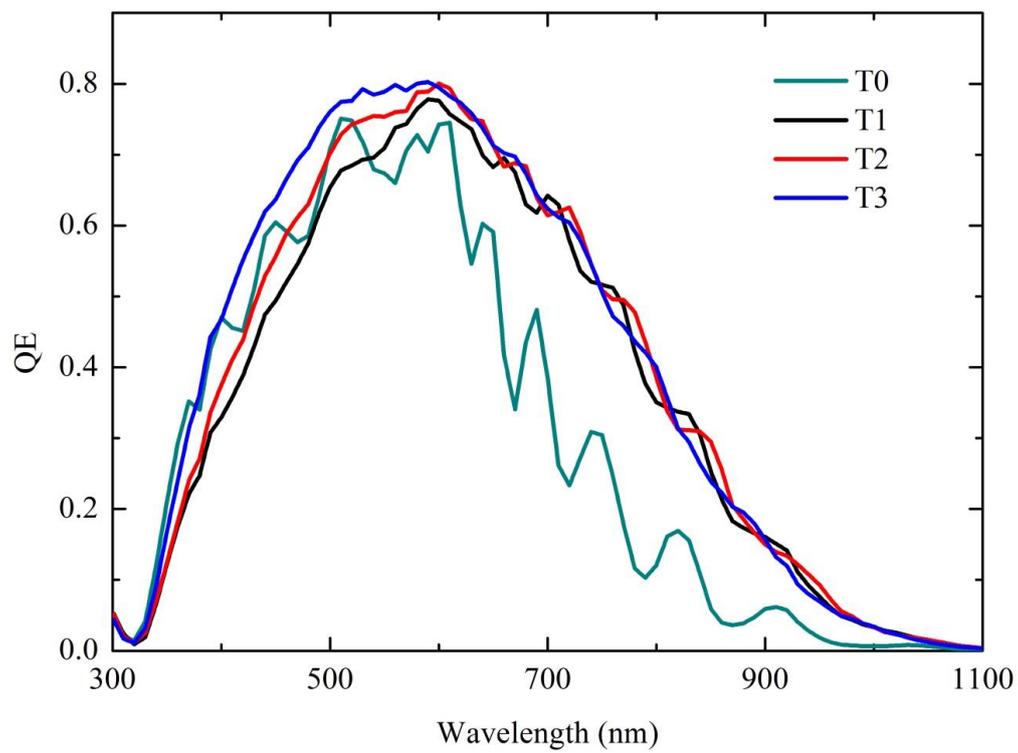


Figure 6

