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DEVELOPMENT OF HIGH PERFORMANCE INDUSTRIAL TCO GLASS FOR VERY LARGE AREA a-Si:H PV MODULES

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ABSTRACT: The European project HELATHIS, executed by the five project partners signing this article, is dedicated to the improvement of the efficiency of very large area (5.7m^2) silicon thin film photovoltaic (PV) modules. Optical confinement has been identified by the project partners as a major source for efficiency improvement of thin film silicon PV modules. One reason of the performance gap between highly efficient laboratory solar cells and industrial modules is the poorer electrical and optical performance of the industrial TCO-covered front glass substrate (TCO glass) which is investigated in this work. The glass substrate in industrial PV modules is about 3 times thicker than in laboratory solar cells where frequently Asahi U-type TCO glass (about 1 mm thick) is used. Therefore, the glass quality has an important impact on the transmission of industrial TCO glass. Reducing the iron-content in the float glass substrate increases the integrated transmission in the wavelength range from 400-800nm by nearly 2%. The electrical properties, namely the electrical carrier mobility, of the industrial TCO layer of AGC has been increased by about 15% by improving the industrial deposition process, resulting in a thinner TCO layer with higher transmission by maintaining the sheet resistance of about 9-10 Ω/sq. Combining both developments the integrated transmission of industrial TCO glass has been increased by more than 2%. The TCO layer properties of Asahi U-type and standard industrial TCO glass (AGC AN10) have been investigated by SEM, AFM, XRD and ARS, showing that the Asahi U TCO scatters red light more effectively into larger angles.

Keywords: a-Si:H, TCO Transparent Conductive Oxide, Thin Film Solar Cell, Optical Properties, Electrical Properties, Morphology

1 INTRODUCTION

Since January 2010 the European project HELATHIS [1] is executed by the consortium created by T-Solar Global S.A., manufacturer of amorphous silicon (a-Si:H) thin film photovoltaic (PV) modules, AGC Flat Glass Europe (AGC), producer of transparent conductive oxide covered float glass ("TCO glass"), the Inst. of Energy and Climate Research 5 at the Research Centre Juelich, the Debye Inst. at the Utrecht University and the Dept. of Applied Physics and Optics at the University of Barcelona. An important objective of the HELATHIS project is the improvement of the light confinement in industrial very large area (2.6 m x 2.2 m, 5.7m^2) a-Si:H PV modules. A big difference in the short circuit current density of high efficiency laboratory solar cells and industrial a-Si:H modules results from the poorer optical and electrical performance of standard industrial TCO glass. The latter is fabricated in large scale in traditional float glass lines while the laboratory solar cells are prepared on optimized TCO glass substrates, like Asahi U-type TCO glass (Asahi), fabricated on small scale with a special procedure. AGC has recently up-graded their deposition technology for in-line TCO deposition in large scale float glass production to close the performance gap between industrial TCO glass and laboratory glass substrates. During the execution of the HELATHIS project improvements have been achieved on the TCO properties and on the glass quality.

In this work we compare the physical properties of the Asahi-U TCO glass with standard industrial TCO (AGC AN10) and present first results on newly developed improved industrial TCO glasses for very large area application. AGC recently has introduced a TCO glass with lower iron content (ANS-type) for a-Si:H application and has developed a TCO layer with enhanced carrier mobility (ME-type) which both are combined by the new TCO glass type ANS10ME.

We have investigated TCO-layer properties by Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and X-Ray Diffraction spectroscopy (XRD) and correlate these results with optical measurements from Transmission Spectroscopy and Angular Resolved Scattering (ARS). Furthermore, the electrical properties of TCO layers have been determined by Hall-effect measurement.

2 RESULTS / DISCUSSION

2.1 TCO morphology

A visual impression of the surface morphology of the Asahi and the industrial AN10 TCO layer is given by the SEM images shown in Fig. 1. Both TCOs present a random surface texture however the crystallites of the Asahi TCO are better defined with plane surfaces and sharp edges, while the AN10 crystallites have a rough surface and rounder edges.

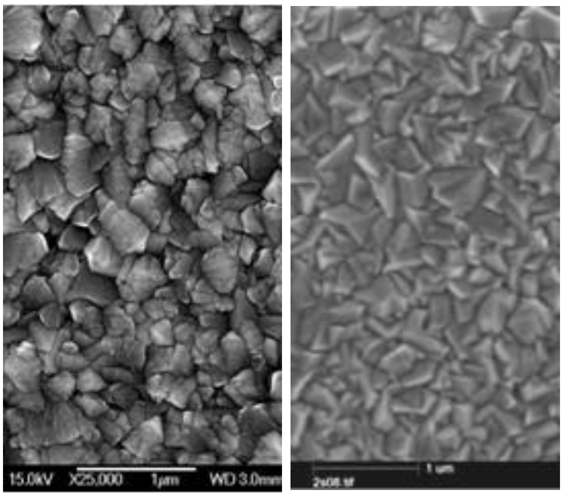

Figure 1: SEM pictures of AGC standard industrial TCO AN10 (left) and Asahi TCO (right) indicated a difference in the surface properties of the crystallites.

Information about the crystal structure of both TCOs was determined from XRD spectra, where the absorption peaks corresponding to different crystal orientations have been analyzed. Fig. 2 shows the distribution of the integrated intensity of the major seven crystal plane orientations found in the XRD spectra and Fig. 3 the average size of the corresponding crystallites. The Asahi TCO presents in bigger crystallites than AN10 with the biggest ones for the 220 orientation, however with the smallest frequency.

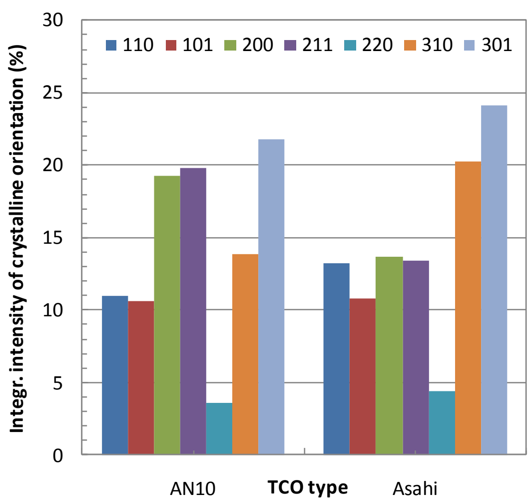

Figure 2: Comparison of the crystalline structure of AN10 and Asahi TCO layer from XRD spectroscopy present slight differences in the intensity distribution. The legend indicates the crystal plane orientation.

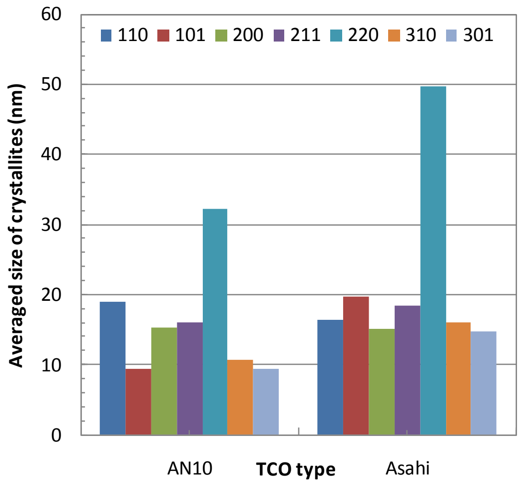

Figure 3: Comparison of the crystalline structure shows in general bigger crystallites in the Asahi TCO. The legend indicates the crystal plane orientation.

To get more information about the impact of the different surface morphology on the optical properties of both TCOs, the AFM images shown in Fig. 4 have been prepared. The AFM pictures were statistically analyzed resulting in a RMS roughness of about 47nm and 29nm and a total height of the topography of 341 and 257nm for Asahi and AN10 respectively. Furthermore, a Fourier analysis of the surface topology has been performed [2] to get information about the scattering properties. In Fig. 5 the intensity of scattered light calculated with the phase model [2, 3] is presented together with experimental data from ARS (see also Fig. 7). To make the data of both approaches comparable, the data of the ARS measurements has been normalized to the maximum found for scattering angles around 20-50^{o}and the AFM data, presenting some spikes due to the finite sampling size and the periodic boundary in the FFT, has been adjusted in the maximum by a NLLS-fit to match with the maximum of the experimental data.

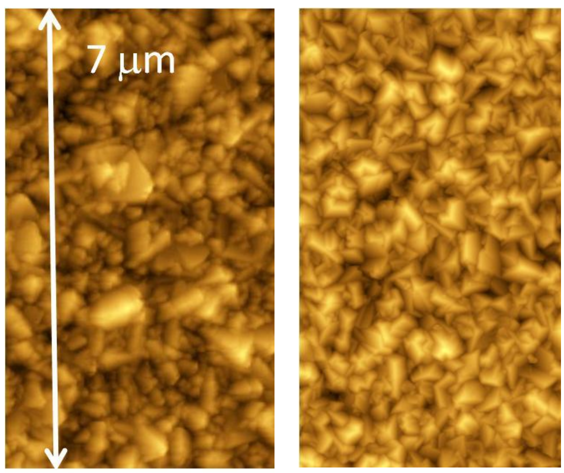

Figure 4: AFM pictures of AGC AN10 (left) and Asahi U (right) provide more detailed information about the surface properties by Fourier analysis of the surface topology as shown in Fig. 5.

After these adjustments the agreement between experimental and theoretical data is very good and demonstrates that the surface structure of the Asahi TCO scatters the red light into large angles than the AN10 TCO. This happens at the TCO/air interface which is easy to measure, however in the solar cell the light scattering occurs at the TCO/a-Si:H interface which is hard to measure. For evaluation of the scattering phenomena at the TCO/a-Si:H interface the application of the theoretical model by exchanging the optical properties of air by the ones of a-Si:H, will help to better understand the scattering in real solar cells.

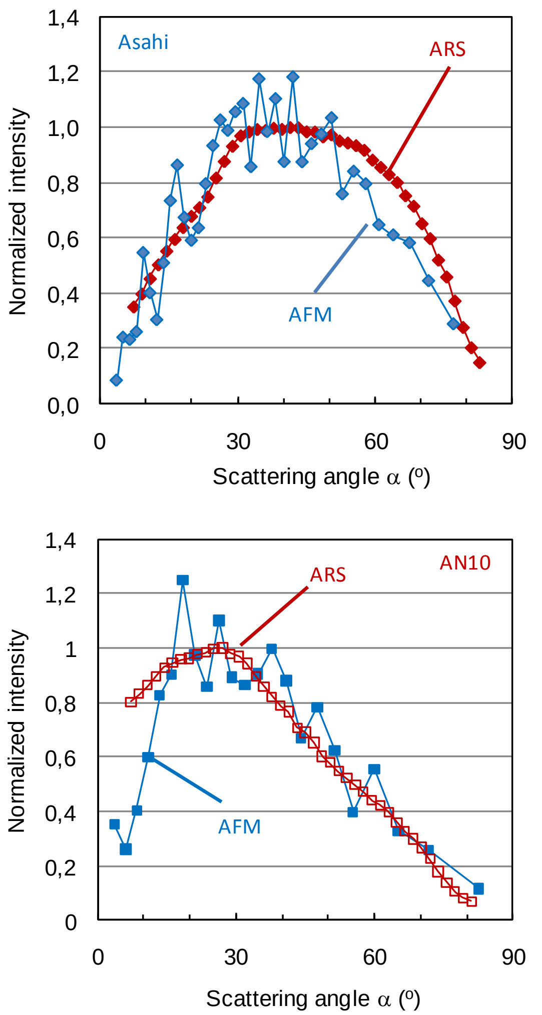

Figure 5: Fourier transform intensity for different scattering angles calculated from AFM images of Fig. 4 agrees well with the intensity of ARS measurements (see. Fig. 6). The comparison of Asahi (top) and AN10 TCO (bottom) presents different light scattering properties (wavelength range 633nm).

2.2 Optical properties of TCOs

Fig. 6 shows the optical transmission of the TCOs Asahi, AN10 and the new developed ANS10ME in the wavelength range from 400-800nm interesting for single junction a-Si:H solar cells. In Table I the values of integrated transmission of these TCOs and in addition values of ANS10 and AN10ME TCO, TCOs from intermediate development steps, are presented. The standard industrial TCO glass AN10 fabricated in-line on standard float glass presents about 1.5% less transmission in comparison to the Asahi TCO glass. The low iron substrate glass ANS10 presents already similar high optical transmission as Asahi TCO glass. In AN10ME TCO glass AGC has further improved the electrical properties of the TCO layer (see Table II), achieving a thinner TCO layer with similar sheet resistance of 9-10 Ω/sq but with higher transmission than AN10. The newest TCO glass generation ANS10ME combines the low iron substrate with improved ME TCO layer (last row in Table I) resulting in better optical performance than Asahi TCO glass.

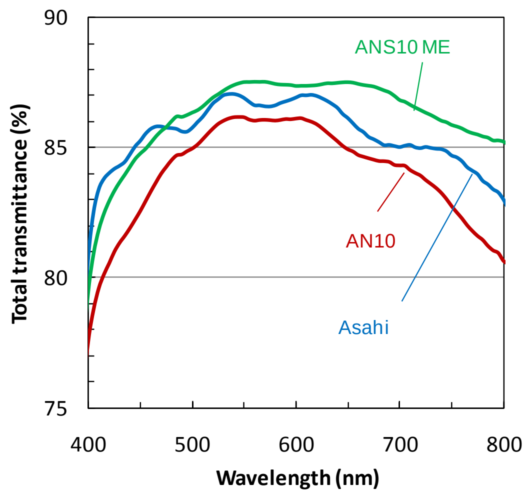

Figure 6: Comparison of the transmission of Asahi TCO glass (blue, glass thickness 1.1mm) and industrial TCO glasses (glass thickness 3.2 mm) AN10 (red) and the new improved ANS10ME TCO glass (green). Combining properties of low iron glass with recently developed ME TCO layer results in better optical performance than Asahi TCO glass. The measurements were done with index matching liquid CH_2I_2 and a 3 mm quartz plate.

Table I: Typical values for the integrated transmission of TCO glasses calculated in the wavelength range from 400 to 800 nm (with application of index matching liquid).

Sample	Integr. total transmission (400-800nm, %)	Δ to AN10
Asahi	85,4	1,5
AN10	83,9	
ANS10	85,6	1,7
AN10 ME	84,6	0,7
ANS10 ME	86,1	2,2

Fig. 7 compares angular-resolved scattering data of Asahi and AN10 TCO glass. The measurements are done with the standard goniometer setup illuminating the sample with a small laser spot at λ = 633 nm from the glass front side and monitoring the transmitted scattered light intensity, E(α, λ), with a photodiode covering the area a. Then, the total light intensity, S(α, λ) at every angle α scattered into the half space is calculated by integration over the solid angle:

$$S(\alpha,\lambda)= \frac{E(\alpha,\lambda)}{E_R\,(\alpha,\lambda)\ a}\ 2\pi d^2\,\Delta\alpha \sin\alpha$$

where $E_R(\alpha,\lambda)$ is normalization factor and Δα the step width of the angle calculated from the width of the photo diode and the distance, d, between TCO glass and photo diode.

The comparison of the data shows that the scattered light intensity for angles below 50° is significantly larger for AN10 resulting in a higher haze as compared to Asahi. The surface structure of the Asahi TCO scatters light in the red wavelength range (here 633nm) into larger angles which is favorable for thin a-Si:H solar cells resulting in a longer path length for absorption. However, as already mentioned this is the case for the TCO/air interface while the scattering properties at the TCO/a-Si:H interface are still under investigation.

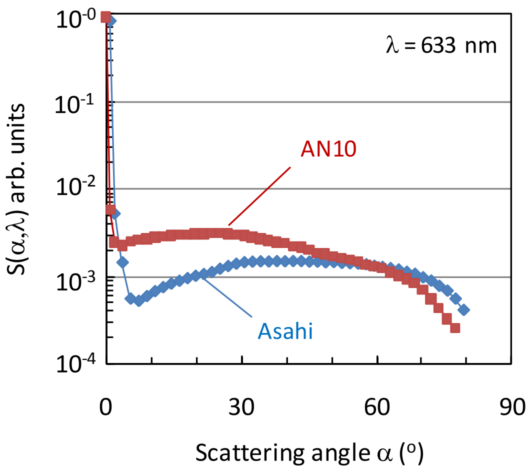

Figure 7: The comparison of the light scattering of the Asahi and AN10 TCO indicates stronger scattering into larger angles in the red wavelength range (here 633nm) for the Asahi TCO.

2.3 Electrical properties of TCOs

The electrical properties of the TCO layers of the Asahi and the industrial TCOs of AGC are summarized in Table II. While the electrical properties of the Asahi and AN10 TCO are rather similar, the carrier mobility of the ME-type TCO is about 15% higher than the one of the standard AN10. This permits to reduce the TCO layer thickness from about 1μm to about 750 nm maintaining the sheet resistance of the layer in the range of 9-10 Ω/sq. The thinner TCO layer thickness results in about 0.7 % higher integrated transmission in the wavelength range from 400-800nm as shown in Table I.

Table: II: Specific charge carrier density, n, carrier mobility, μ, and specific resistivity, ρ, of Asahi, AN10 and AN10ME TCO layer.

	Asahi	**AN10**	**AN10 ME**
n (10^{20} cm^{-3})	3,19	3,11	3,08
μ (cm^2/Vs)	28,6	27,8	31,9
ρ (10^{-3} Ω*cm)	0,69	0,72	0,64

3 CONCLUSION

The morphology of Asahi U-type TCO glass, frequently used for high efficient laboratory a-Si:H silicon solar cells, and industrial AN10 TCO glass presents differences in their surface topology resulting in stronger light scattering into large angles in the red wavelength (633nm) of the Asahi U TCO. The comparison of the light transmission of Asahi U-type TCO glass and industrial TCO glasses shows that by reduction of the iron content in the float glass substrate the performance gap between both TCO glasses nearly can be closed. Further improvement of the industrial TCO glass has been achieved by a new deposition process increasing the electrical carrier mobility in the TCO-layer (ME-type TCO layer). Combining both developments increases the integrated transmittance in the wavelength range from 400-800nm, most interesting for a-Si single junction solar cells, by more than 2%, resulting in better optical performing industrial TCO glass than the Asahi U-type TCO glass. The impact of mobility enhancement on TCO-layer properties and on solar cell, respectively PV module performance, is still under investigation.

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HELATHIS-project web pages: www.tsolar.com/helathis