NANO-IMPRINT TECHNOLOGY COMBINED WITH ROUGH TCO MORPHOLOGY AS DOUBLE TEXTURED LIGHT-TRAPPING SUPERSTRATE FOR THIN FILM SOLAR CELLS

M. Steltenpool[1], E. Moulin[2], F.J. Haug[2], M. Ghosh[3], M. Meier[3], J. Rutten[1], M. Bos[1],
G. van der Hofstad[1], A. Tavakoliyaraki[1], and A.J.M. van Erven[1]
[1)] OM&T B.V., High Tech Campus 29, 5656AE Eindhoven, The Netherlands
[2)] EPFL/IMT, Rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland
[3)] IEK5-Photovoltaics, Forschungszentrum Jülich GmbH, Jülich, 52425, Germany

ABSTRACT: Two types of nano-imprinted 2D grating textures were tested on their light trapping performance for thin film Si tandem solar cells in combination with various TCO's. The combination with rough TCO layers like LPCVD ZnO leads to double textured superstrates that exhibit at least a similar light trapping capability as the state-of-the-art reference while using thinner TCO layers. Further optimization in combination with nano-imprinted AR textures on the air/glass interface has the potential for >13% devices with thin TCO and absorber layers.
Keywords: Light trapping, Thin film Si, TCO, Texturisation

1 INTRODUCTION

Nano-imprinting technology has recently gained interest due to its potential to further reduce the cost per watt-peak of thin film solar cells, which is a prerequisite in order to remain competitive with wafer-based crystalline silicon solar cells. By use of nano-imprint technology, a low-cost textured glass superstrate can be obtained with excellent light-trapping properties which allows for thinner absorber layers. It also eliminates the need for thick and therefore absorbing TCO's, for which a sufficient thickness is required to achieve the desired surface texture.

OM&T | Moser Baer Technologies has developed periodically textured glass superstrates by use of nano-imprinting technology which have been specifically designed to scatter light efficiently in combination with the random native roughness of the TCO layer. By tuning the imprinted 2D periodic texture shape and the TCO layer thickness the light-trapping ability is significantly improved resulting in an increase of the Jsc of thin film silicon tandem solar cells. The textures were also developed to minimize the risk of micro-crack formation in the μc-Si layer which can result in electrical losses (FF and Voc).

The European FP7 project "Fast Track", in which OM&T is partner to develop a large area industrial nano-imprint process, is a consortium with leading industry partners and research institutions that has the goal to go beyond the current status of thin film solar cell technology. Within the framework of this project a comparison has been made between different textured TCO superstrates, such as as-grown random LPCVD ZnO (EPFL), random wet-chemically etched ZnO:Al (Jülich), nano-imprinted periodically textured superstrates with ZnO:Al (OM&T) and the random TCO morphology superimposed on nano-imprinted superstrates (double textures). This paper presents the first results of this comparison.

2 EXPERIMENTAL

Two types of nano-imprinted gratings have been used for these trials. One (P800) with a relatively shallow 2D periodic reference texture with a period of 800 nm and a height of 120 nm that is typically used as a "working horse" texture at OM&T because of its tolerance for process variations; and a second one with a period of 1200 nm and height of 320 nm (P1200) that is more optimized for high bottom cell currents and should be used in combination with relatively rough front TCO's. Figure 1 shows a schematic cross-section of these two types of nano-imprinted 2D gratings in combination with a smooth (left) and rough (right) TCO layer.

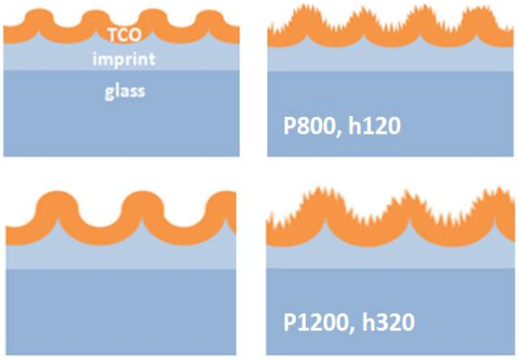

Figure 1: Schematic cross-section of the used samples with examples of smooth (left) and rough (right) TCO

At OM&T these samples were used in combination with sputtered ZnO:Al (98:2 composition sputter target) without post treatment.

Jülich typically uses sputtered aluminium doped ZnO followed by HCl wet etching (sputter-etched AZO) as a reference process [1] which results in relatively large features (high FF and Voc, acceptable current). Subsequent etching by HF results in the incorporation of smaller features that can boost the current of the top cell. Figure 2 shows examples of HCl etched (left) and HCl + HF etched (right) TCO samples.

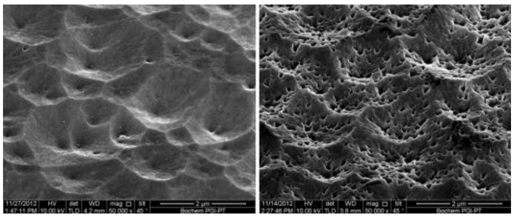

Figure 2: Sputtered AZO etched by HCl (left) and by HCl + HF (right)

For these first trials Jülich used either a thin sputtered ITO or AZO layer on the imprinted gratings, experiments with subsequent wet chemically etching will be carried out at a later stage.

EPFL uses LPCVD boron doped ZnO as a reference process which can provide smaller and larger features, also depending on the layer thickness [3-5]. Such samples typically exhibit very good light-trapping characteristics which result in a high Jsc with acceptable FF and Voc. Subsequent Ar-plasma etching can be used in order to round-off the sharp features which increases the FF and Voc at the cost of some Jsc. Figure 3 shows examples of LPCVD ZnO:B with smaller (left) and larger (right) features.

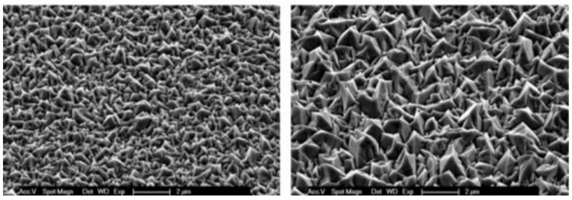

Figure 3: EPFL LPCVD ZnO

For these trials the group at EPFL coated the periodically textured substrates first with a highly conductive thin In_2O_3:H layer to meet the sheet-resistance requirement. On top of the thin IOH layer either a 30 nm ZnO:Al was sputtered as protective layer and/or a non-intentionally doped highly transparent LPCVD ZnO layer is deposited with a thickness of 500 and 1000 nm and corresponding increased roughness.

All TCO coated nano-imprinted 2D grating samples were characterized by SEM and/or AFM and used as superstrates for a-Si:H/µc-Si:H tandem solar cells. The resulting cells were characterized by IV and EQE measurements.

3 RESULTS AND DISCUSSION

3.1 Results OM&T

Figure 4 shows SEM pictures of the two substrate types after sputtering of AZO layers with a varying thickness.

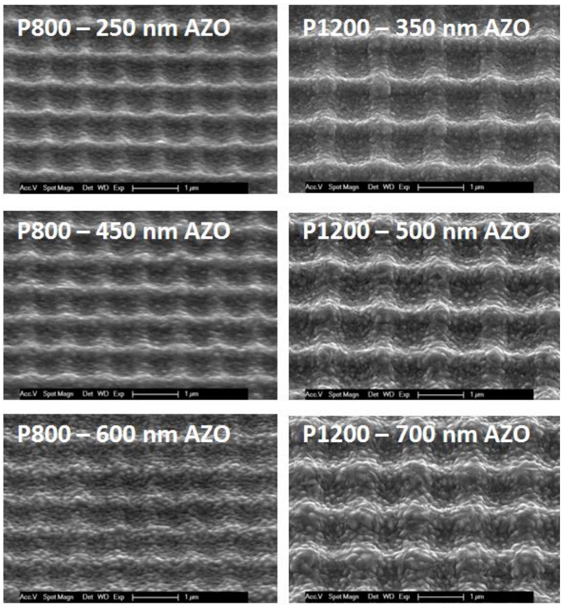

Figure 4: 2D Gratings with sputtered AZO

It can be seen that the surface morphology changes as a function of TCO thickness. The roughness increases with thicker AZO layers and also the duty cycle of the texture increases (ratio of feature size to pit size).

Figure 5 shows EQE measurements of a-Si:H/µc-Si:H tandem solar cells processed at OM&T on the P1200 texture compared with the results of using a random SnO2:F (FTO) reference. The tandem cells consisted of a 225 nm a-Si:H top cell, a 1200 nm µc-Si:H bottom cell (with no intermediate reflector) and an AZO/Al back contact.

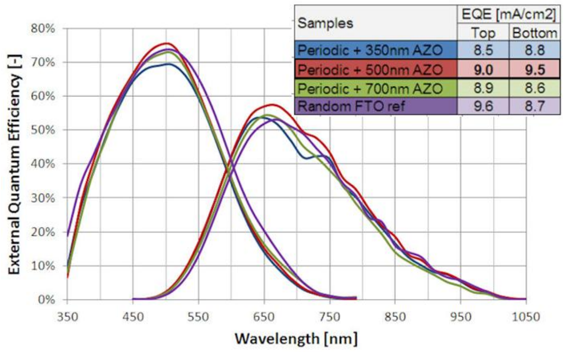

Figure 5: Corresponding EQE measurements P1200

The EQE measurements show large differences in both top- and bottom cell response. The a-Si:H top cell appears to profit from the additional native roughness of the sputtered AZO layer. The µc-Si bottom cell response peaks at an AZO thickness of 500nm. More information on these results can be found in reference [2].

3.2 Results Jülich

Figure 6 shows AFM line-scans of the bare P800 (left) and P1200 (right) texture and coated with a thin ITO or AZO layer. The thin TCO layers have a very limited effect on the original texture height and duty-cycle.

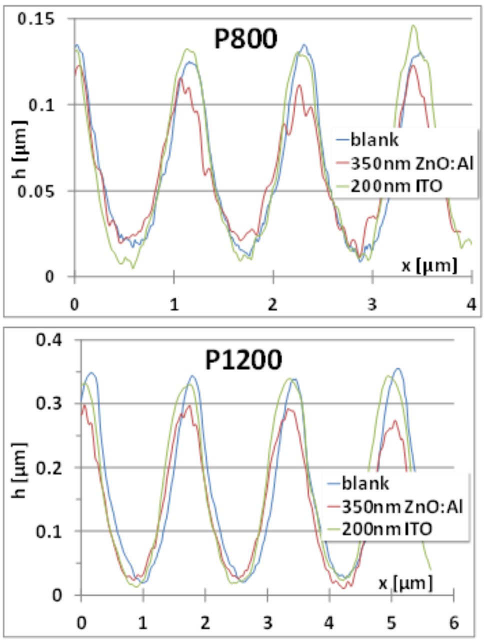

Figure 6: Diagonal AFM line scans of the bare P800 (left) and P1200 (right) texture and coated with a ITO or AZO layer

Figure 7 shows the EQE measurements of the Si tandem solar cells deposited on these samples.

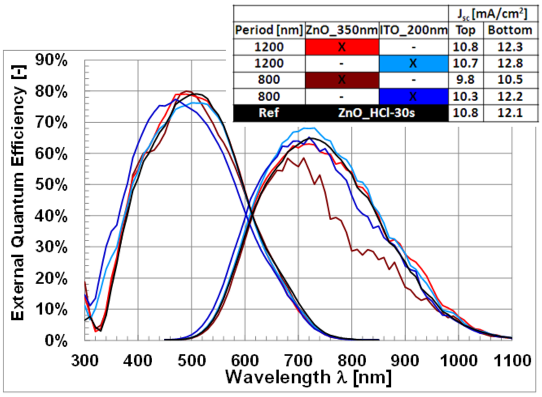

Figure 7: EQE of tandem solar cells grown on (with ITO or AZO) coated P800 and P1200 texture (Ref: tandem cell on sputter-etched ZnO)

The EQE measurements show the potential of using such 2D grating superstrates exhibiting high bottom cell currents with acceptable top cell currents which can be tuned by optimizing texture period and height. The combination with such a smooth TCO results in good electrical properties, however, some extra roughness could be beneficial for finding the optimal trade-off in top and bottom cell currents in combination with good FF and Voc. This can be further explored by adding an HCl and/or HF wet etching step after AZO sputtering.

3.3 Results EPFL

Figure 8 shows SEM pictures of the two substrate types after coating the samples with a thin IOH and either a 30 nm sputtered ZnO:Al or non-intentionally doped LPCVD ZnO layer with a thickness of 500 or 1000 nm.

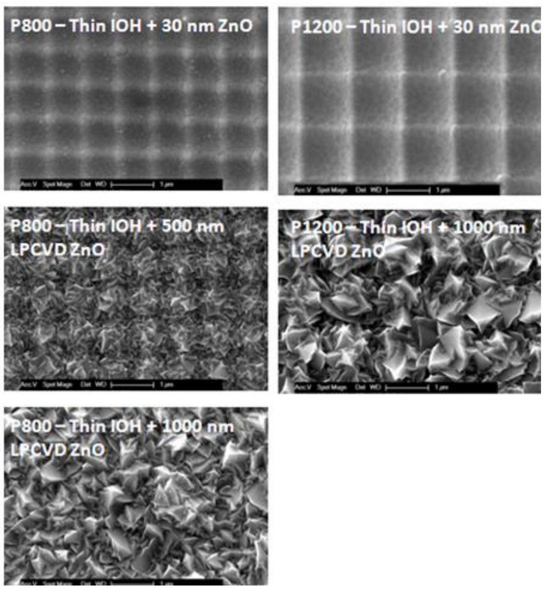

Figure 8: 2D Gratings with thin IOH and LPCVD ZnO

The 2D grating texture is still clearly present after the deposition of 30 and 500 nm LPCVD ZnO but is completely leveled for both the P800 and P1200 texture coated with 1000 nm ZnO. The obtained roughness however of the 1000 nm LPCVD ZnO is already comparable with LPCVD reference layers that require 2 to 3 times such a layer thickness in order to obtain such large features.

Figure 9 shows the EQE results of micromorph silicon tandem solar cells deposited at EPFL on the P1200 samples including an intermediate reflector and using LPCVD ZnO as back reflector. Also the EQE measurement of a cell deposited on a bare glass reference with 500 nm LPCVD ZnO is included for comparison as well as the results of the state-of-the-art EPFL reference which is a 2.5 micron LPCVD ZnO layer post-treated with 4 minutes of Ar-plasma (Z2.5 4’).

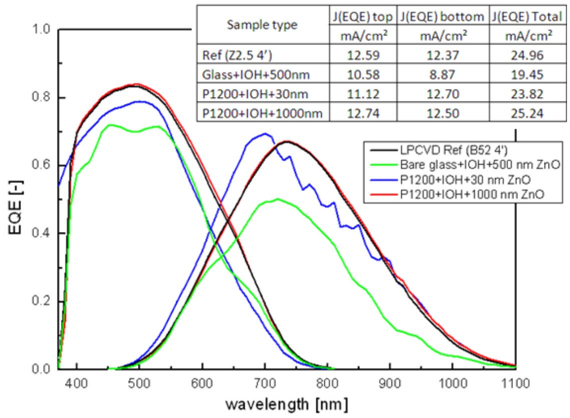

Figure 9: EQE of Si tandem cells from EPFL

Table II shows the corresponding IV results.

Table II: IV results EPFL

Sample type	Jsc	Voc	FF	Eff
	mA/cm²	(V)		(%)
LPCVD Reference (Z2.5 4’)	12.37	1.35	0.72	12.03
Bare glass + IOH + 500 nm LPCVD ZnO	8.87	1.37	0.52	6.36
P1200 + IOH + 30 nm ZnO	11.12	1.40	0.71	11.01
P1200 + IOH + 1000 nm LPCVD-ZnO	12.50	1.32	0.69	11.45

The P1200 sample with 30 nm ZnO shows a relatively low top cell and high bottom cell current density which is a similar behaviour as the OM&T and Jülich samples with thinner TCO layers. This is typical for these types of nano-imprinted 2D grating samples in combination with a relatively smooth TCO. The bottom cell current of this sample exceeds the corresponding value of the LPCVD Z2.5 4’ reference but this is related to the poor response of the top cell rather than to good collection of IR light. However, when depositing a 1000 nm LPCVD ZnO layer on the P1200 sample the top cell current gets a boost from the extra scattering introduced by the rough TCO layer. P1200 plus 1000 nm LPCVD ZnO yields double textures that exceed the EQE performance of the reference.

The poor performance of the bare glass sample with 500 nm LPCVD ZnO compared with a 1000 nm layer deposited on a P1200 sample demonstrates somewhat the difference in LPCVD ZnO growth morphology on different samples. Rough TCO layers are more easily achieved on textured samples, which allows for using relatively thin TCO layers in order to obtain the required light-trapping textures.

The IV results show a decreasing FF and Voc with increasing LPCVD ZnO thickness on the P1200 samples which is attributed to the increased roughness. The efficiency values are influenced by the amount of mismatch between the top and bottom cell currents although the P1200 + 1000 nm ZnO is quite nicely matched, resulting in an efficiency only slightly lower than the state-of-the-art reference. The lower FF and Voc could be mitigated by using a short Ar-plasma post-treatment which reduces the “sharpness” of the features. This could lead to a somewhat lower Jsc due to a reduced light trapping functionality but this negative effect can be prevented by also using nano-imprinted AR textures on the air/glass interface [6]. The complete stack can subsequently be optimized incorporating the various light trapping technologies (double textured superstrates, AR textured glass, SiOx p- and n-layers, ...) which will lead to >13% efficient thin-film Si devices. Together with the superior low light performance and superior temperature coefficient of thin film Si solar panels which both lead to higher kWh/kWp ratio’s, thin-film Si PV can become again a competitive player.

7 CONCLUSION

- Nano-imprinted 2D gratings in combination with various types of TCO’s were successfully used as superstrates for thin film silicon solar cells
- The grating parameters like period, height, shape and duty cycle can be optimized for different device requirements
- Using textured substrates by nano-imprinting allows for thinner TCO layers as the texture requirements are already (partially) fulfilled by the imprinted layer
- The combination of optimized 2D gratings and smooth TCO’s results in solar cells with a relatively high Voc. High top cell currents are more challenging
- The combination of optimized 2D gratings with rough TCO’s results in double textured superstrates which exhibit relatively high current densities
- These double textured superstrates can be tuned in combination with AR textured glass to find the optimum (ultimate) trade-off in top and bottom cell currents *and* high FF and Voc in combination with lower cost thin TCO and absorber layers

8 ACKNOWLEDGEMENTS

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