HIGH-PERFORMANCE AR COATING ON GLASS APPLIED USING HIGH-PRESSURE MOLDING

J. Jong[1], E. Brouwer[1], V. Rosca[2]*, A.R. Burgers[2], A.J. Carr[2], L.A.G. Okel[2]
[1] TOWA Europe B.V., Geograaf 14, 6921 EW Duiven, The Netherlands
[2] ECN Solar Energy, Westerduinweg 3, 1755 LE, Petten, The Netherlands
*Corresponding author. E-mail: rosca@ecn.nl

ABSTRACT: Herein we report on the development and testing of a high-performance structured AR coating applied to solar glass by means of TOWA's high-pressure molding technology. This technology allows the application of optically-active structures on glass with unprecedented freedom of geometry and precision. The structured layer with AR functionality were based on a theoretically defined geometry, which then was translated into a mold design. As deduced from the systematic I-V measurements at different angles of incidence, the developed ARC provided a ca. 2.1% rel. gain in I_{SC} at normal incidence and greatly improved light capturing at high angles of incidence as compared to flat glass, but also compared to a typical commercial structured solar glass. The experimentally-derived incident angle dependence was then used to estimate the impact of ARC on annual yield for a typical residential system. Depending on the location and the system orientation the ARC improves the annual yield by 5-7% rel. when compared to a flat glass-black background configuration and by 2-2.5% rel. when compared to a flat glass-white background configuration. Aside from greatly light trapping, the coating could offer additional advantages, like improved aesthetics, protection against mechanical impact, and electrical safety of a module and could benefit such applications as BIPV, automotive PV, portable PV, space-based PV.
Keywords: Light trapping, antireflection coating, PV module, PV system, Manufacturing and processing

1 INTRODUCTION

Past experience has shown that anti-reflective coatings (ARC) on glass can improve light coupling, particularly under high angles of incidence. This is especially interesting for panels with a fixed mounting, which are the vast majority of modules. An ARC will enhance energy yield when the sun is not at an optimum position relative to the panel, which, for some systems is the majority of the time. In this paper we report the main results of a study aimed at using high-pressure molding technology, developed by TOWA, to form a high-performance ARC on glass and in this way increase the energy yield of the module at minimum cost increase.

TOWA's molding technology is suitable for the encapsulation of LEDs and electronic components in general. The LEDs are encapsulated as a complete wafer whereby the encapsulant can be formed into the shape of a lens at the location of each individual LED. The shape of the lens can be tuned by changing the design of the mold used during the encapsulation process. Lenses can be made to focus the light produced by the LED or make it diffuse. The key advantage of this molding technology is the great precision and freedom of geometry of the molded structures (see Fig. 1). It is thought that the high-pressure molding technology can be scaled up to the size required for coating a sheet of glass with the dimensions of a full-sized module (approximately 1×1.6 m).

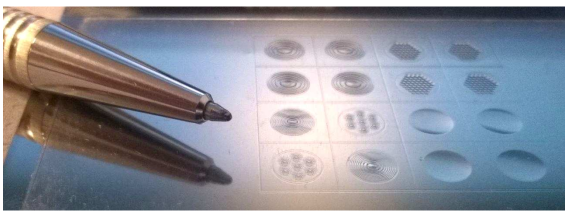

Figure 1: Examples of structures that can be produced using TOWA's high-pressure molding technology.

In this project we made use of the design flexibility offered by TOWA's molding technology to develop a high-performance ARC on glass, which would allow capturing most of the light that is normally lost in state-of-the-art PV panels. In this project we took the complete route from defining optically-active structures by means of ray tracing and then translating the theoretically-defined geometries into a mold design, to producing coatings on glass, the experimental evaluation of the developed coatings, and finally calculation of the impact of the developed structured on the annual yield for a typical residential PV system. Herein we describe main results and conclusions of the project, with focus on manufacturing of the test samples and evaluation of the optical performance of the developed AR coating. The evaluation of the optical performance included systematic I-V measurements at various angles of incidence and annual yield calculation for typical residential systems using PVsyst simulation software.

2 METHODS AND PROCEDURES

In this section we describe the procedure for application of the optically active coatings on glass substrate, manufacturing and testing of single-cell modules, and the annual yield calculations methodology. The geometry of the structures responsible for the AR effect was thoroughly optimized by means of optical modelling, but the results of this theoretical work will be reported elsewhere.

2.1 Application of AR coating

The optically-active coatings on glass were obtained by means of high-pressure molding process using TOWA's CPM 1080 molding system. A dedicated modular mold, carefully selected separation foil, and a commercial silicone compound had been used to produce coated solar glass samples. The molding process closely resembled an industrial high-pressure molding process for encapsulation of micro-electronic devices. An additional ex-situ post-curing step was introduced in order to ensure the optimal degree of cross-linking of the compound. The glass substrate was a 200×200×4mm solar glass sheet and an area of approx. 145×145mm area was covered by optically-active structures. Therefore, the area above the (6-inch) cell was not completely covered with ARC. The resulting coating consists of an array of dome-shaped lenses (see Fig. 2). The lenses are not stand- alone objects: there is a very thin underlying continuous layer of molding compound connecting all lenses.

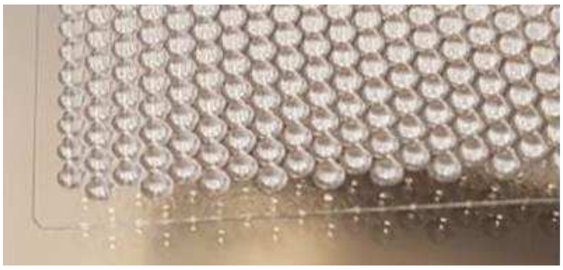

Figure 2: A close-up photograph of TOWA's structured AR coating on a solar glass substrate.

2.2 Manufacture of single-cell modules

In order to experimentally evaluate the effect of the TOWA coating, the coated glass samples were used to manufacture single-cell PV modules. In principle any type of PV cell and module interconnection method could be used to evaluate the effect of the coatings. However, we decided to use the interdigitated back-contact (IBC) cells. The main advantage of using IBC cells is the absence of metallization on the front of the cell (sunny side). In this way complications related to the presence of the front metallization are avoided. This allowed a more straightforward evaluation of the beneficial effect of the coating.

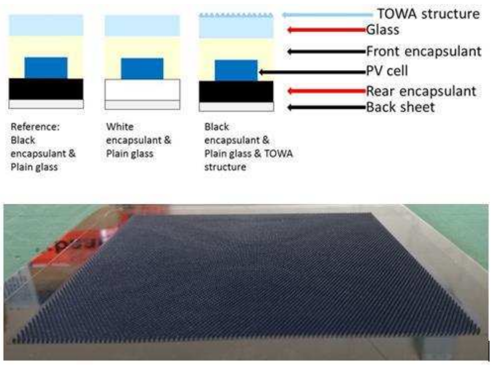

Figure 3: Single-cell laminate lay-outs manufactured and tested (top) and photograph of an IBC module having black rear encapsulant and glass coated with TOWA's AR coating (bottom).

The modules used for evaluation of the performance of AR coating were manufactured using the pilot back-contact module assembly line supplied by Eurotron B.V. (The Netherlands) using commercially available module materials (conductive back-sheet foil, electrically conductive adhesive, and EVA encapsulants) and a standard module manufacturing process practiced at ECN. Cells were ECN's Mercury IBC cells with Sirius interconnection design [1].

Prior to module manufacturing, the stability of the molded layer was tested by means of repeated lamination trials. Although thermal stability of the layers was not expected to be an issue, there might be a risk of some deformation of the layer under pressure during the lamination step. Therefore, especially designed Teflon spacers were developed in order to limit the pressure applied to the coating, but still ensure good mechanical contact and heat exchange with the whole glass area.

Three types of modules were manufactured and tested: (1) modules having black rear encapsulant and flat glass, (2) modules having white rear encapsulant and flat glass, and (3) modules having black rear encapsulant and glass with TOWA's AR coating. See Figure 3. The I-V characteristics of all modules were measured under various angle of incidence, as described in the next section.

2.3 I-V measurements

The optical performance of the developed AR coating was evaluated by means of systematic I-V measurements of the single-cell IBC modules. The I-V measurements under standard test conditions (STC) and at varied angle of incidence were carried out using PASAN IIIb flash tester (class-A according to IEC 60904-9). Firstly, all modules were measured under STC and then cell-to-module losses were calculated from cell I-V data acquired with same flash tester and under same conditions. Secondly, the I-V data was acquired under various angle of incidence. The angle of incidence was controlled by means of a dedicated in-house developed setup. This setup was thoroughly tested and adjusted to provide reliable and repeatable measurements [2]. To ensure significance of the effect of the angle of incidence on the module power output, at least three modules were measured per group.

Importantly, the modules were masked using black tape in order to expose the same aperture area for all modules. Tape was applied at a distance of 1.25 mm from the cell edge, which is typical inter-cell distance for back-contact modules.

2.4 Annual yield calculations

In order to assess the potential impact of the developed AR coating on the system level and compare to other module configurations, annual yield calculations were carried out using the PVsyst software [3]. PVsyst applies an Incidence Angle Modifier (IAM) based on the ASHRAE model to each module, unless a specific IAM has been defined for the module [4]. The IAMs for each module lay-out were calculated from experimentally obtained current values after normalization and cosine correction. Annual yield calculations were performed for three different system orientations and three locations (see Table 1).

Table 1: System variations: location, tilt angle and orientation.

Location	Tilt angle	Orientation
Amsterdam	38° (optimum)	South
	60°	South
	90°	West (façade)
Kyoto	30° (optimum)	South
	60°	South
	90°	West (façade)
Doha (Qatar)	25° (optimum)	South
	60°	South
	90°	West (façade)

For the PV component a 5kW system has been chosen consisting of 18×280W SolarWorld Sunmodule SW280 panels and a Fronius International 5kW Primo 5.0-1 inverter. This module was used as the basis for the flat glass-white back sheet module. We have then adjusted the module parameters to obtain realistic versions of the module with the flat glass and the black encapsulant, and for the TOWA ARC and black encapsulant configurations. These calculations were based on the measured results at STC (at normal incidence) of the single-cell modules. The modules also include an IAM particular to the given module.

3 RESULTS AND DATA ANALYSIS

3.1 Characteristics of AR coating on glass

Figure 2 shows a picture of a solar glass sheet with AR coating. The coating showed exceptionally good adhesion to glass and aesthetically improved appearance. The parameters of the molding process as well as the separator foil had to be optimized in order to obtain defect-free coating. The coating consisted of ca. 12000 individual lenses.

Due to some practical considerations, the roughness of the surface of individual lenses was sub-optimal and that could have negatively impacted the optical effect. Furthermore, due to practical consideration, the cell area could not be completely covered, which diminished the overall effect.

So far no reliability studies have been carried out on the modules built with TOWA's AR coatings. However, we have carried out TC200 and DH1000 tests (IEC61215) on glass samples coated with a thin (0.25 mm) continuous flat layer of the same compound on glass. The coated glass samples were exposed to TC200 and DH1000 tests (IEC61215), with visual appearance, adhesion (cross-cut), and transmission measurements (integration sphere) as characterization methods before and after accelerated stress tests. For DH1000 samples we observed very limited loss of transmission, hardly any change in visual appearance, but some loss of adhesion (delamination for 20-25% of cross-cut area). For TC200 samples we have observed full retention of adhesion, no visual changes and very limited change in light transmission. Screening of various molding compounds to improve the coating weathering characteristics is in order.

Table 2: Comparison of cell-to-module Isc change for modules with the three configurations.

Code	Glass / background	Rel. cell-to-module Isc change (%)*	
		Avrg	SD
B	Flat / black	0	0.06
B-AR	AR coat. / black	+2.13	0.07
W	Flat / white	+3.38	0.10

* Compared to modules with flat glass and black rear encapsulant.

3.2 Optical performance at STC

Table 2 compares cell-to-module (CTM) change for the modules having three configurations at STC conditions (normal incidence). CTM losses were calculated from the experimental data for at least three modules. The cell data measured under identical conditions and same flash tester. The module in which AR coating is combined with black background shows a significant I_{SC} gain, which is still ca. 30% lower than the gain observed for flat glass-white background configuration. Note, however, that the AR coating was optimized to improve light collection under a broad range of angles of incidence and ultimately improve annual yield.

3.3 Optical performance at varied incident angles

The optical performance of various module configurations at varied angles of incidence can be compared using derived IAM values for each module configuration. Such a comparison is shown in Fig. 4.

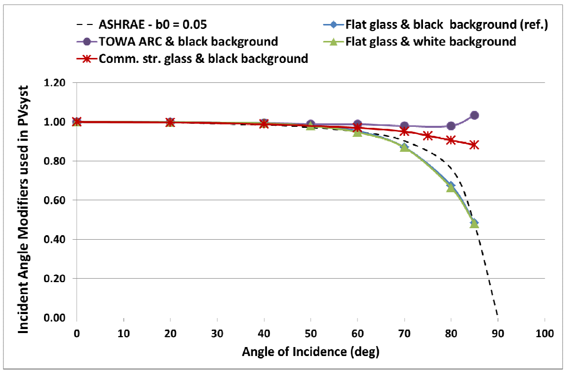

Figure 4: Measured Incident Angle Modifiers (IAMs) for a fixed azimuth, compared to the standard ASHRAE – b_0=0.05 used in annual yield simulations; also included is a previously measured IAM for a commercial structured glass.

TOWA's structured AR coating shows a great improvement when compared to flat glass, but also a significant improvement when compared to a very good commercial structured glass recently tested at ECN. Note that the commercial structured glass was measured using different cell and glass (at an earlier stage and not part of this experiment), hence we could not proceed with proper comparison on the system level. Interestingly, IAM values measured for TOWA's coating at grazing angles exceeding the value of one. The effect is reproducible and is currently being investigated.

The AR effect of the TOWA's coating is determined primarily by the geometric effect. At the same time, the refractive index of the compound (as given by the supplier) is 1.41. which means that an index-matching effect should also have a contribution.

Finally, note that the performance of TOWA's ARC is even more impressive if we take into account that the coating was not fully optimized from both geometry and processing points of view (see subsection 3.1).

3.4 Effect on annual yield

Before we proceed with presentation and discussion of annual yield data, it is important to mention that in this study we focused on evaluation of the optical effect of the developed ARC itself. For that purpose flat glass-black background configuration was chosen as reference. The flat glass – white background configuration was another configuration we have included because (i) this configuration provides a simple and inexpensive way to boost the module current and (ii) we could prepare and test the required samples without difficulties. Although we had planned benchmarking on the system level against commercial structured glass products and other AR coatings on flat glass, it was not possible to obtain required samples in the required format (1-cell module) and determine IAM for the same cell and module bill of material.

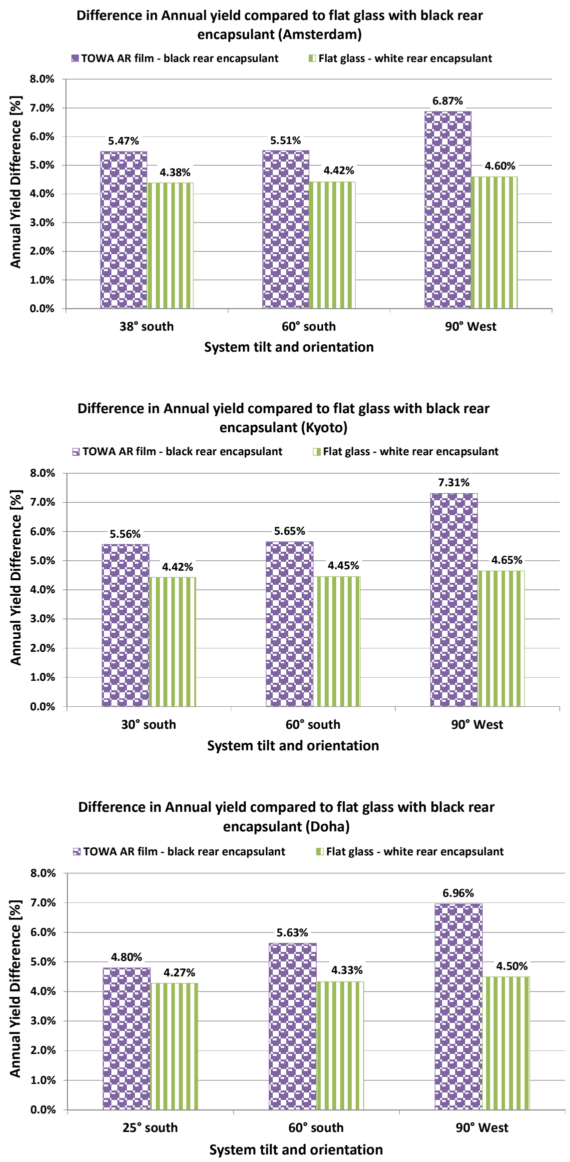

Figure 5. Overview of relative difference in annual yield for three glass-encapsulant combinations, three locations and three orientations.

Turning now to presentation and analysis of the results, the relative differences in annual yield calculated for the three module configurations are presented in Figure 5. The flat glass - white background configuration brings an angle-independent improvement over the flat glass - black background reference, whereas TOWA's AR coating gives an improvement over both black- (5-7% rel.) and white background (2-2.5% rel.) configurations for all locations and orientations, with a prominent angle-dependence effect, as expected. Accordingly, from the monthly yield data (not shown) for the 38° and 60° orientation, TOWA's ARC improves yield significantly in spring-autumn period, whereas for the 90° facing a dramatic increase in yield is observed for winter months over the white background configuration. In other words, the further from optimal tilt angle for given location, the higher the gain and beneficial effect of the coating.

As for potentially interesting practical applications of the proposed technology, TOWA's AR coating should allow replacement of the flat glass - white background configuration with TOWA ARC – black background configuration (required from aesthetical considerations, for example) without loss and even with a gain in annual yield. Furthermore, colored compounds can be used to improve the visual appearance of the module with minimum performance loss. Naturally, the TOWA's ARC could be an interesting alternative to commercial structured glasses or AR coatings on flat glass and can be combined with white background to achieve exceptional cell-to-module current gains.

4 CONCLUSIONS

Herein we reported on development and testing of high-performance AR coating applied to solar glass by means of TOWA's high-pressure molding technology. This technology allows the application of optically-active structures on glass with unprecedented freedom of geometry and precision. As deduced from the systematic I-V measurements at different angles of incidence, the developed ARC is responsible for ca. 2.1% rel. gain in I_{SC} at normal incidence and greatly-improved light capturing at high angles of incidence as compared to flat glass, but also to a typical commercial structured glass. The experimentally-derived incident angle dependence was then used to estimate the impact of ARC on the annual yield. The TOWA's structured ARC improves the annual yield by 5-7% rel. as compared to flat glass-black background configuration and by 2-2.5% rel. as compared to flat glass – white background configuration, depending on the location and system orientation. Importantly, the above results although impressive already were obtained for a not fully optimized coating. Aside from greatly enhanced light trapping on module level, the coating could contribute to improved aesthetics, protection against mechanical impact, and electrical safety of the module and could benefit such application as BIPV, automotive PV, portable PV, space-based PV.

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