Presented at the 40th European Photovoltaic Solar Energy Conference and Exhibition, 18-22 September 2023, Lisbon, Portugal

IMPROVEMENT OPTIONS FOR PV MODULES BY GLASS STRUCTURING

Marc Hofmann[1], Laura Stevens[1], Patrick Hör[1], Philipp Barth[1], Benedikt Bläsi[1], Stephan Riepe[1], Svenja Kalthoff[1], Bishal Kafle[1], Martin Zimmer[1], Max Mittag[1], Sebastian Nold[1], Ilker Sen[2], Johanna Reck[3], Nikolas Schröer[4], Laurent Clochard[5], Sebastian Ihlow[6], Carsten Horch[6]
[1]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany
[2]Gebr. Schmid, Robert-Bosch-Str. 32-36, 72250 Freudenstadt, Germany
[3]SENTECH Instruments, Schwarzschildstr. 2, 12489 Berlin, Germany
[4]ICB, Ludwig-Erhard-Ring 21, 15827 Dahlewitz, Germany
[5]Nines Photovoltaics, Synergy Centre TU Dublin- Tallaght Campus, Dublin 24 D24 A386, Ireland
[6]GMB Glasmanufaktur Brandenburg, Spremberger Str. 4, 03130 Tschernitz, Germany
Tel.: +49 761 4588-5051, email: marc.hofmann@ise.fraunhofer.de

ABSTRACT: The structuring of glass surfaces offers a wide area of application for photovoltaics: Increasing the energy yield and decreasing glare are achievable and become important factors for applications to building surfaces like roofs facing north, façades or walls along streets (e.g., noise-barrier). We investigated ways to reach specific glass surface morphologies and optical behaviors using wet and dry etching, combinations of blasting and etching, and imprinting into hot glass. We found that when a structured glass surface is present at the solar module's front, an increase in electricity yield can be achieved, with the largest gains under angles of incidence above 60°. Also, the application of structured glass to the solar module's rear can have a positive impact on the performance; we saw an increase in energy yield with illumination from the front especially for angles of incidence of 40° and above. The glass surface properties were investigated using a newly setup laser-based measurement tool that helped understanding light diffraction.

Keywords: module glass structuring, glass imprinting, glass etching, module performance improvement.

1 INTRODUCTION

Photovoltaic module glass surface structuring offers the chance to engineer the optical properties of reflection and transmission of light at and through the glass. Such treated glasses could provide higher electricity generation of the encapsulated solar cells and reduce glare effects. This would allow the extensive use of building envelopes that are not in consideration yet due to either lower electrical performance (e.g., roofs facing northern directions) or that would lead to significant glare issues (e.g., façades near public streets, …). It was shown that, in Germany, the relevant shares of existing building envelopes would allow for about 1 TW of PV installation [1]. Figure 1 brings together the findings of Wirth [2] with building-integrated photovoltaics' (BIPV) potential being in the range of 1 TW. Additionally, other already-mankind-treated areas in Germany hold significant PV-integration potential.

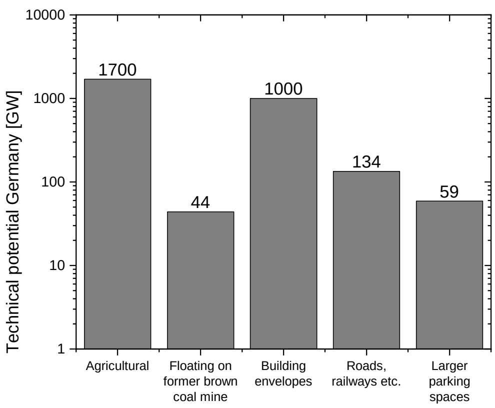

Figure 1: Technical potential for integration of PV in already existing human land use in Germany. Data taken from [2].

Performance increase and cost considerations allow the determination of the impact a certain improvement or cost change might have. In Figure 2, we used ISE's cost calculation tool SCost [3]. For example, increasing the electricity yield by 0.15%$_{abs}$ would allow a decrease in levelized cost of electricity (LCOE) by about 0.01 €ct/kWh. In other words, higher area-related costs of 0.8 €/m2 would theoretically be possible leading to the same LCOE.

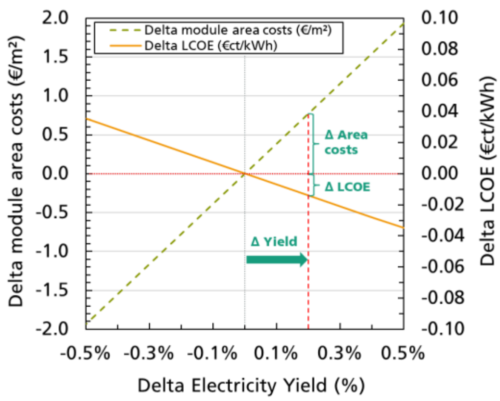

Figure 2: Calculation of interdependence of total cost, electricity yield and LCOE.

The structuring of glass surfaces is a promising way to reduce glare, increase performance and, as a result, enlarge the application possibilities of PV modules.

Glass structuring was investigated before. The company Saint-Gobain has offered structured glasses under the product name Albarino [4]. Such glasses were successfully tested in indoor and outdoor conditions as presented by Grunow et al. [5] who showed efficiency gains for the modules.

In the approach presented here, we are working on different technologies to achieve structured glass surfaces that facilitate optical reflection and transmission engineering in a solar PV module. Etching of (rather) cold glass is performed. Etching was carried out using two different approaches: wet chemicals or dry gases. Besides

or prior to the etching, the effect of an additional blasting treatment was evaluated. Surface structure results are characterized with a newly designed measurement tool that analyses the diffusivity of the light transmission through a treated glass.
The current state of the art to improve light absorption is to texture the surface of the solar cell and apply an anti-reflective layer on both solar cell and glass of the module. Structuring the glass itself could generate further electric gains, increasing efficiency, but also further facilitate the application of PV modules by reducing angular dependence and glare. Huge potential for PV incorporation is found in building surfaces. Mostly, houses are currently only using roof areas facing south directions due to highest PV electricity harvesting. Roofs facing north and façades could provide a large share of electricity generated by BIPV, but the glare effects affecting the vision of e.g., car drivers passing by are an issue. Moreover, for Agrivoltaic (APV) more and more upright installations (fence-style) are considered. Additionally, for all application surfaces and tilting angles of modules, an increase of light absorption in the solar cells due to glass structuring would be a benefit, especially for shallow angles of incidence.

2 SIMULATION OF GLASS SURFACES

Optical simulations of glass surfaces included into photovoltaic modules were performed.
Here, one focus was put on the structuring of the front glass surfaces of glass-glass modules. Significant yield gain can be expected from a structured glass surface, according to the simulation results, presented in Figure 3.

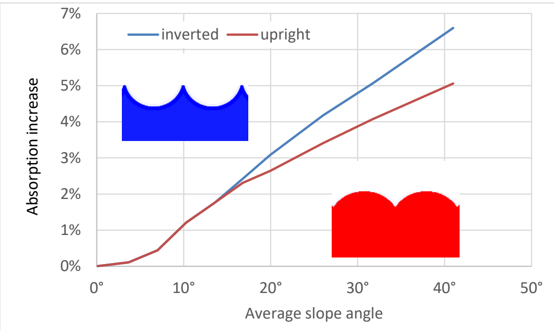

Figure 3: Estimation of the yield enhancement that can be achieved by texturing the front surface of the module glass. As a simple model, the increased optical in-coupling caused by spherical caps (inverted and upright) was modeled using the SunSolve raytracer of PV Lighthouse [6]. The simulation based on diffusely incident radiation gives a good first estimate for the enhanced annual yield. Especially the inverted spherical caps with their “bowl-like” shape are beneficial, since their steep sidewalls couple in light incident at shallow angles.

A simulation study on structured glass surfaces for the application as rear module surface is presented by L. Stevens et al. within this conference [7].

3 ETCHING OF GLASS SURFACES

For the structuring of glass, wet and dry etching technologies were evaluated.
First, we want to report on the wet etching process development. Here, one important goal was to increase the process speed. Currently, we achieved a process duration of about 3 min to end up with the surface structure presented in Figure 4. The etching process bath includes hydrofluoric acid plus additives and is performed in the acidic regime. Next steps in our work will include the upscaling of the etching process to larger glass surfaces.

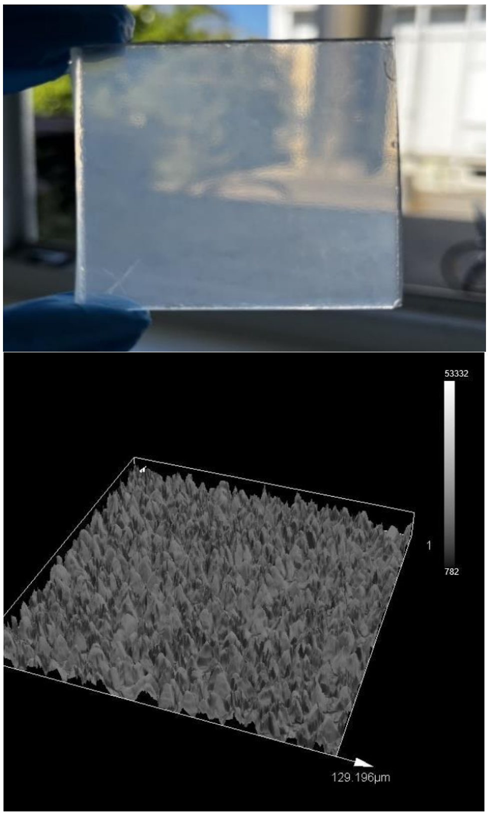

Figure 4: Example results of a wet-etched glass surface.
Top: Photo of a treated glass.
Bottom: Confocal microscopy image of a treated glass surface.

Dry technologies can also be applied to etch glass surfaces. NinesPV and Fraunhofer ISE worked on the development of a plasma-free dry etching process. Figure 5 gives an example of glass surfaces after dry etching. Here, the thermally driven etching process based on climate-friendly F_2 gas led to the creation of a nanoporous layer at the glass surface. Transmission can be improved with an antireflective layer created by this etching. The etching depth corresponds to the wavelength showing the peak in transmission (optical depth ≈ $\lambda/4$). It was found that the structures we could achieve applying the dry etching approach differed significantly from the structures reached with the wet-chemical processes within the investigated parameter ranges.

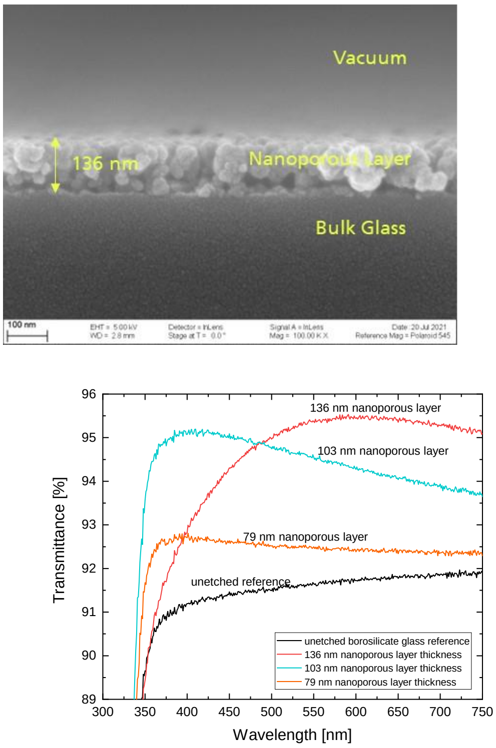

Figure 5: Results after dry etching of glass using a plasma-less process applying climate-friendly F_2 gas.
Top: Scanning electron microscopy (SEM) image of nanoporous layer etched into the surface of a glass sample.
Bottom: Transmittance data showing the increase by etching a glass surface. The transmittance peak shifts with the depth of the porous layer. The peak for sample exhibiting the 79 nm nanoporous layer is expected to be in the wavelength range dominated by the lower transmission of the glass.

4 BLASTING PLUS ETCHING

Besides solely etching glass surfaces, Schmid and Fraunhofer ISE have evaluated the combination of blasting a glass surface with subsequent wet etching. This approach allows a larger degree of freedom for the engineering of glass surface shapes. Figure 6 shows the surface angle distributions of 3 “blast plus etch” processes and an “only etch” sample for comparison in a histogram-style representation. The more area portions with higher surface angles are detected in this measurement, the more light incident from shallow angels can be in-coupled (compare to Figure 3).

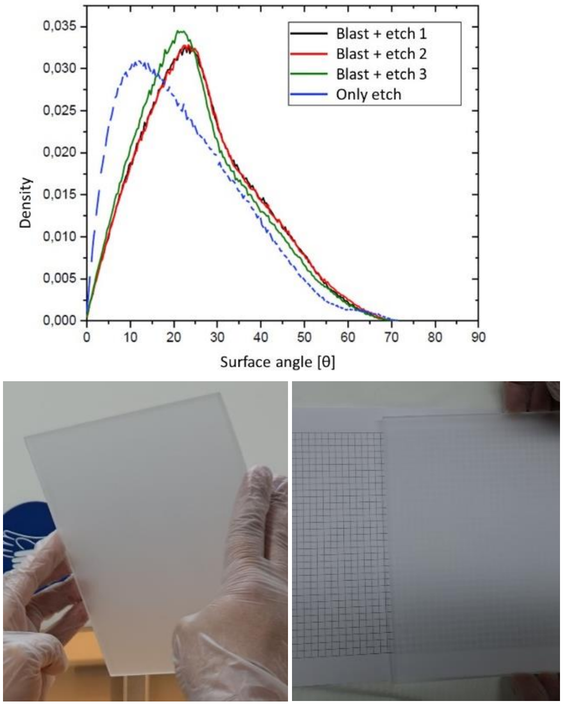

Figure 6: Results of blasted plus wet-etched glass.
Top: Surface angle distribution of wet-etched and blasted plus wet-etched glass.
Bottom: Photographs of blasted plus wet-etched glass sample with homogenous structuring.

5 IMPRINTING IN HOT GLASS

The production of flat glass starts with the mixture of the ingredients. Then, the heating-up to transfer into the liquid phase takes place, followed by a cooling-down. While the glass is still hot, the imprinting of structures into the glass surface can be facilitated. By these means, the company GMB is already manufacturing different products. We have investigated novel structures to improve the optical performance of solar modules. In cooperation of GMB and Fraunhofer ISE, a back-sheet solar glass with specialized optical properties was developed by raytracing simulations and optical measurements of the incident lights. In order to implement the proposed glass structures into the glass production process and produce the narrow and small glass structures, a significant amount of pre-work was performed. In a duplex iteration process GMB explored the necessarily needed hot end parameters as glass temperature, roller pace, annealing lehr’s conditions etc. for the best outcome of the glass structures’ dimension values in order to produce the solar glass as close to the simulated glass structures (around hundredths of a millimeter) in terms of dimensions as possible on an industrial scale. This produced glass has unique optical properties as a better light incident from the backside of the backsheet over all incident angles, which leads to a higher luminous efficacy and yield of the solar panels.

6 MEASUREMENT OF OPTICAL PROPERTIES

Within our work, a novel measurement tool was developed by Sentech, analyzing the light scattering taking place while light transmits through a structured glass sample. A quantification of the scattering that is achieved can be made and thus a comparison of samples on this basis is possible. Figure 7 (left) shows the principal setup of the measurement tool and an exemplary 2D diffraction image.

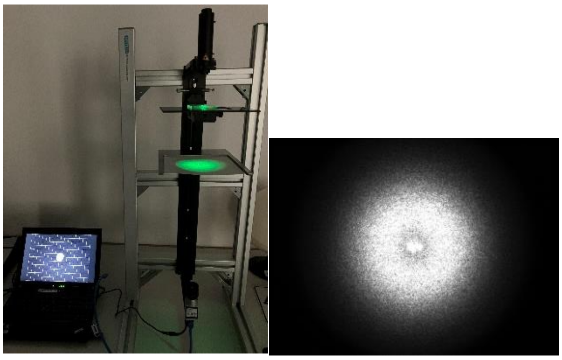

Figure 7: Left: Setup of light diffraction measurement tool. Right: Example 2D diffraction image achieved using the novel tool.

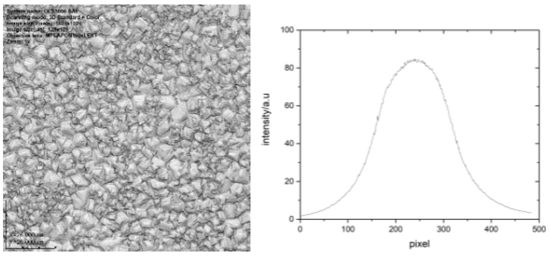

Figure 8: Right: example measurement results of diffracted light achieved using the novel measurement tool. A line scan of the light diffraction distribution is shown. Here: relatively homogeneous structuring was achieved. Left: confocal microscopy image of the same sample.

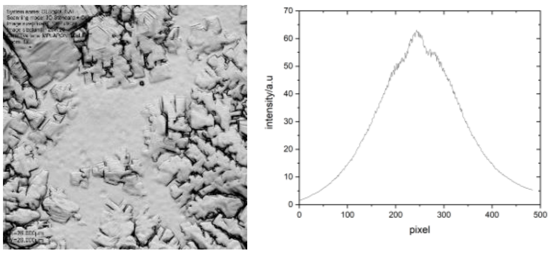

Figure 9: Right: Example measurement results of diffracted light achieved using the novel measurement tool. Here: relatively inhomogeneous structuring was achieved with significant area shares being rather flat leading to a peak in the measurement signal. Left: confocal microscopy image of the same sample.

Figure 8 and Figure 9 show exemplary measurement results of structured glasses applying the novel measurement tool in comparison to confocal microscopy images. One can see that the line scans of the diffraction pattern depend on the homogeneity of the glass structure distribution.

7 IMPLEMENTATIONS INTO SOLAR MODULES

Structured glasses were implemented into small solar modules to investigate the related electrical performance (200x200 mm^2). In the characterization of the solar modules, special care was taken of the performance under different angels of incidence θ. To compare the results, the "incidence angle modifier" IAM was calculated from the short-circuit current densities of the modules and the correction factor cos(θ):

$$IAM = \frac{Isc(\theta)}{\cos(\theta) * Isc(0)}$$

Figure 10 shows IAM values for differently structured small solar modules. The top graph was created using solar modules with differently structured module front glass and with illumination from the front. We can see that the unstructured reference glass performs about the same as the structured counterparts up to an angle of 50°. Then, with increasing angle of incidence, structured glasses show benefits, with the blasted-plus-etched glasses leading to the highest gains under high angles, outperforming the "only-etched" samples. Imprinted glasses were not tested here.

Figure 10 (bottom) shows results of the application of a flat front with a variation of the rear glass, applying an illumination from the front. Thus, investigating the effect on the internal rear reflectance. Here, the structured rear glass showed improved module performance already starting at an angle of ~40°. In contrast to Figure 10 (top) is the bottom graph looking at average values of 3 identically prepared mini modules of each kind. Here, the highest short-circuit current density (J_{SC}) at perpendicular incidence of each kind of module was used as reference (100%).

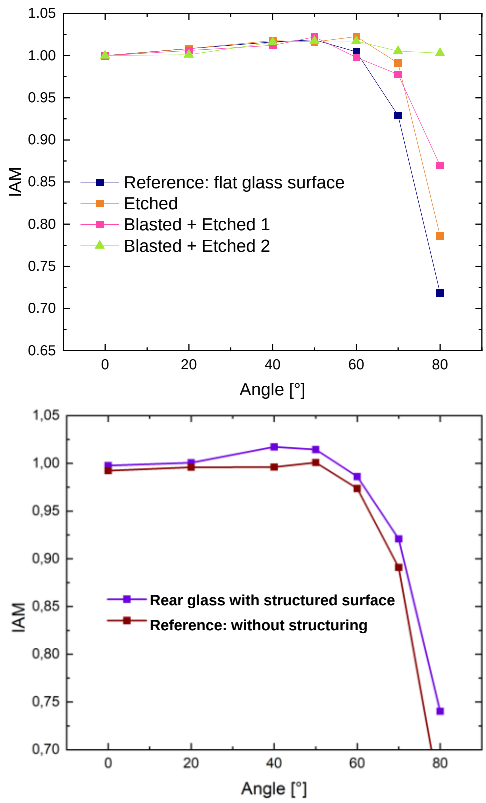

Figure 10: Top: IAM of differently structured module front glasses. Bottom: IAM of module rear glass with or without structuring.

The benefits of structured glass result from a reduced reflection especially at higher angles of incidence (Figure 11, a, Figure 10) of the glasses as well as an improved internal light management (Figure 11, d). Due to the expectable non-perpendicular irradiance of light on the rear side of the module the additional gains are likely for bifacial modules (Figure 11, c). An increase of reflection at perpendicular irradiance (Figure 11, b) might reduce the power of the module at Standard Testing Conditions (STC) thus increasing the necessity to assess the module regarding performance i.e. using extended simulation [8], energy rating [9] or other advanced yield calculation methods. However, using the investigated glass structures, no decrease of module power was measured at perpendicular irradiance for most of the investigated samples.

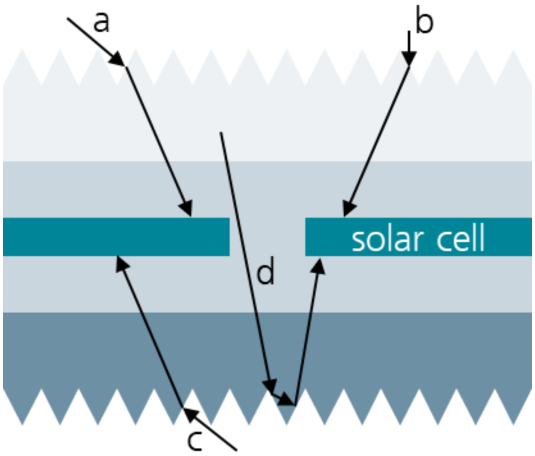

Figure 11: Schematic of light paths impacted by structured glass covers.

8 SUMMARY

Glass structuring by different means is capable of leading to benefits in the solar module performance. It was shown that imprinting into hot glass, etching the glass or blasting plus etching glass can show improvements in the energy yield. This is especially due to improvements in the reflection properties of the glass for angles in the range of ~60° or higher, a region where the incidence angle modifier of the flat reference glass typically drops sharply.

Acknowledgements

This work was funded by the German Federal Ministry for Economic Affairs and Climate Action within the research project "OPTOMOD" (contract no. 03EE1079A).

References

[1] Eggers J-B, Behnisch M, Eisenlohr J, Poglitsch H, Phung W-F, Münzinger M, Ferrara C, Kuhn T, PV-Ausbauerfordernisse versus Gebäudepotenzial: Ergebnis einer gebäudescharfen Analyse für ganz Deutschland, 2020, 35th PV-Symposium, Bad Staffelstein, pp. 837-856

[2] Wirth H, Recent Facts about Photovoltaics in Germany, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/recent-facts-about-photovoltaics-in-germany.pdf, accessed on 26 January 2023.

[3] Nold S, Techno-ökonomische Bewertung neuer Produktionstechnologien entlang der Photovoltaik-Wertschöpfungskette: Modell zur Analyse der Total Cost of Ownership von Photovoltaik-Technologien. Dissertation: Fraunhofer Verlag, 2019.

[4] Blieske U, Doege T, Gayout P, Neander M, Neumann D and Prat A, "Light-trapping in solar modules using extra-white textured glass," 3rd World Conference on Photovoltaic Energy Conversion, 2003., pp. 188-191.

[5] Grunow, P., Sauter, D., Hoffmann, V., Huljic, D., Litzenburger, B., & Podlowski, L. (2005). The influence of textured surfaces of solar cells and modules on the energy rating of PV systems. 20th EPVSEC.

[6] https://www.pvlighthouse.com.au/sunsolve

[7] Stevens, L., Bläsi, B., Horch, C., Ihlow, S., Mittag, M., „Structured Backside Glass for Improved Efficiency in Solar Modules – A Simulation Study", 40th EUPVSEC, 2023.

[8] Pfreundt, A., et al., "Cell-to-module Analysis beyond Standard Test Conditions," *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, Canada

[9] Protti, A., et al. "Virtual Energy Rating: A Method For Optimizing Module Performance Through Cell-To-Module Analysis", 8th WCPEC, 2022