

# Zinc-selective light diffuser for enhanced efficiency and reduced degradation in photovoltaic modules

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## Abstract

This article introduces a zinc metal layer structure integrated into a standard photovoltaic (PV) module, potentially serving a double purpose: as a light reflecting and re-directing diffuser, increasing the PV module overall efficiency, offering anodic protection of Ag/Sn interface against corrosion within the PV module structure. The ethylene-vinyl acetate (EVA) cross-linking degree and peel force measurements were carried out to check the quality of the encapsulation process for the modified modules. Finally, the electrical series resistance of PV modules was measured showing that the modified PV module almost maintained its initial series resistance after exposure to damp-heat conditions of 85 °C, 85% relative humidity for 1000 h, while the unmodified PV module increased its resistance by 5% under the same conditions.

## 1. Introduction

Photovoltaics (PV) is considered to be the most promising solution to answer global energy needs because solar energy is the safest, cleanest, and abundant energy source for future renewable and sustainable energy technologies [1–3]. Silicon-based technology is the mainstream of PVs and will remain dominant in the market in the coming years [4, 5]. Various areas are developing, including building integrated photovoltaics (BIPV), for which glass-glass modules are particularly important [6–9]. The characteristics of the PV market is that the volume of PV panels is expressed in watts of peak power, denoted as “ $W_p$ ” (watt-peak). This is possible because all PV modules are parametrized under standard test conditions. The  $W_p$  is then a derivative of efficiency. The market situation is complemented by PV module lifetime guarantees reaching 20 to even 40 years and yield guarantees reaching 10 to 20 years. Although PV modules are a very reliable source of electrical energy, field results indicate that the modules can fail or degrade in many ways.

Scientists and industries around the world are aiming for higher efficiency at lower costs, as well as increased

reliability. The currently manufactured structures of silicon PV cells are highly optimized, limiting further improvements in their efficiency. In PV modules, these cells are separated and the total area of the spaces between them accounts for approximately 4%. This means that the surface area separating the PV cells is not active in terms of solar energy conversion to electricity. In their previous work [10, 11], the authors demonstrated that the panels efficiency can be enhanced by modifying the areas of PV panels between cells. The authors’ concept involves introducing an optical diffuser into the area between cells. An optical diffuser redirects light from this area to the adjacent PV cells, converting the light energy into electrical energy. The authors have shown that this approach can increase the efficiency of PV panels. This study demonstrates that their proposed method for modifying PV panels does not affect their long-term durability.

## 2. Module construction concept

The concept presented here is based on the idea of increasing the efficiency of a PV module by making better use of the cell spacing and the boundary area of the module,

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using an integrated structure coupling light to the PV cells. The proposed diffuser concept is shown in Fig. 1.

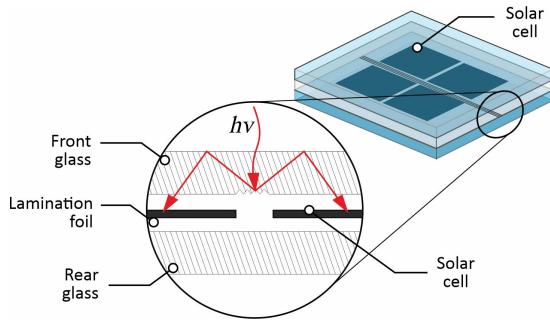


Fig. 1. Graphical presentation of the diffuser concept.

The structure is made using a two-step process based on laser technologies. Step one is engraving a front glass using a continuous wave (CW) CO<sub>2</sub> laser. A set of five parallel grooves with a 500 μm spacing in a 4 mm thick, float, tempered, soda-lime glass was produced with a laser power of 25 W and a scanning speed of 130 mm/s. A detailed description of the process can be found in Ref. 10. Step two used a laser-induced backward transfer (LIBT) with zinc as a reflecting material. The grooves on the front glass were covered by an average thickness 0.5 μm zinc layer using a 1060 nm pulsed wavelength laser with galvo scanning head with an f-theta lens (focal length  $f=245$  mm). The process parameters were set as follows: average power: 30 W, pulse repetition: 55 kHz, scanning speed: 1000 mm/s, cross-hatching pattern with 100 μm spacing and with no gap between zinc donor and glass substrate. LIBT process principle is shown in Fig 2.

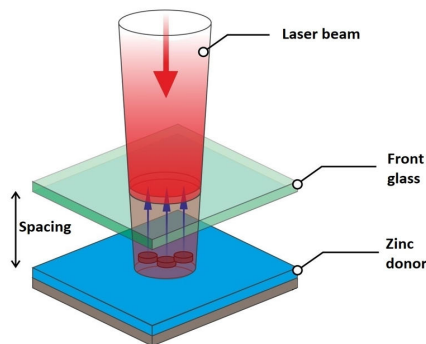


Fig. 2. Illustration of the LIBT process principle.

Details of the process may be found in Ref. 11. Although PV modules are a very reliable source of electrical energy, field results indicate that the modules can fail or degrade in many ways. Three factors may induce cell degradation that lower PV module performance. These factors are increased series resistance ( $R_s$ ), decreasing shunt resistances of the cell, and degradation of an anti-reflection coating (ARC). A high  $R_s$ , which is caused by the degradation of the cell metallization, solder bonds, emitter, and base region, as well as busbars, lowers a voltage at the maximum power point ( $V_{mpp}$ ) and, thus, a fill factor ( $FF$ ) of the cell. The presence of zinc in the PV module structure can have a dual purpose: as a light reflector and anodic protection of the Ag-Sn interface on the ribbon/silicon cell interface, increasing module corrosion resistance [12–14].

### 3. Research and measurements

Durability of the proposed solutions is extremely important. One of the most critical issues is a degree of cure of encapsulant [15]. First tests were carried out on the cross-linking degree of an ethylene-vinyl acetate (EVA) foil, commonly used as encapsulating material in PV industry, using the method described in Ref. 16. Six samples measuring 50 × 50 mm<sup>2</sup> each were prepared in a glass/EVA arrangement with an EVA thickness of 0.45 mm. Lamination of the tested system was carried out using an industrial laminator. To enable a sample extraction, the samples were laminated using an anti-adhesive polytetrafluoroethylene (PTFE) layer. The samples were laminated at 165 °C in a standard industrial process consisting of two stages: foil melting and curing for 420 s and then pressing the laminator membrane for 840 s. A fragment weighing 1 g was extracted from the centre of each sample. The exact weight was determined and marked as  $W_1$ . Samples were placed in a vessel of a known weight. In a separate vessel, 0.0865 g of 2,6-Di-tert-butyl-4-methylphenol (Butylated Hydroxytoluene/BHT) was weighed along with 100 ml of toluene. All ingredients were placed in a vessel with the EVA foil under examination and mixed. The tightly closed vessel was placed in an oven heated to 60 °C for 24 h. The addition of BHT inhibits further EVA cross-linking which could occur at elevated temperatures. Before the end of the sample heating cycle, 65 g/m<sup>2</sup> density filters were dried at 105 °C for 2 h to evaporate the moisture. The filters were then weighed and the values were recorded.  $W_2$  indicates the sum of the weight of the vessel and the filter. The filter was placed in a Büchner funnel and a vacuum pump was connected. The warm solution was filtered through the prepared system. Then the filter with the remaining EVA foil was placed in a vessel and placed in an oven at 105 °C for 4 h. After this time, the sample was taken out and weight  $W_3$  was recorded. The obtained values were inserted into the formula:

$$CLD = \frac{(W_3 - W_2)}{W_1}, \quad (1)$$

where:  $CLD$  – the cross-linking degree [%],  $W_1$  – the sample initial weight,  $W_2$  – the sum of the weight of the vessel and the filter,  $W_3$  – the residual weight of sample with filter and vessel.

Table 1 shows all inputs and cross-linking degree results of the reference samples 1, 2, 3, and modified samples 4,5, 6. Samples 4, 5, and 6 were modified using the two-step laser process described above to obtain a zinc-selective, integrated light diffuser structure.

Table 1.  
EVA cross-linking degree determination.

Sample	$W_1$ [g]	$W_2$ [g]	$W_3$ [g]	Cross-linking degree [%]
1	1.000	139.797	140.647	85.0
2	1.000	139.524	140.382	85.8
3	1.000	130.293	131.152	85.9
4 modified	1.000	131.245	132.108	86.3
5 modified	1.000	138.837	139.685	84.8
6 modified	1.000	130.221	131.081	86.0

The average cross-linking degree of reference samples is 85.56% compared to 85.7%. This indicates that the presence of zinc has no influence on the cross-linking of EVA during the lamination process, and the cross-linking degree remains optimal.

The second important parameter determining the quality of the encapsulation process is adhesion between EVA foil and glass. A test was carried out to confirm the proper adhesion of EVA foil to the modified surface. For this purpose, a PV module sample was prepared using a tempered float glass with a thickness of 3 mm and dimensions of  $200 \times 200 \text{ mm}^2$ . The glass was selectively modified on an area of  $30.15 \times 200 \text{ mm}^2$ . The modification was carried out in two stages: CO<sub>2</sub> laser engraving and zinc coating were applied using the LIBT technique, the parameters being the same for evaluating the cross-linking degree described above.

The sample was prepared in the manner and arrangement shown in Fig. 3.

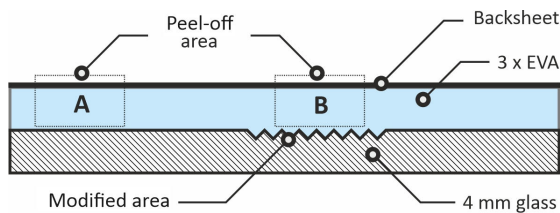


Fig. 3. Sample layout for the adhesion test.

A back sheet foil was used as the upper layer of the laminate. Thanks to this, a typical layer arrangement for PV modules was simulated. In addition, a back sheet foil made of layers of polyester, EVA copolymer, and polyvinyl fluoride (PVF) provided additional mechanical resistance to the layer peeled-off during testing. The system was laminated using an industrial laminator in a two-stage process at a temperature of 165 °C for 420 s of melting and curing the foil and 840 s of pressing the laminator membrane.

The system was then prepared in this way to measure the peel-off force. For this purpose, cuts were made in two areas of the sample: area “A”, where the glass surface was not modified and area “B”, which was modified. The cuts separated a 25 mm wide tape from the remaining surface of the sample. The incision was made up to the glass surface so that the measurement of the breaking force was not disturbed by the measurement of the cohesion force of the foil between the tape and the remaining part of the sample. For each tape, three sections were designated for recording the breaking force. Figure 4 shows the waveforms of the recorded force.

An average value of 128 N was obtained for reference sample “A.” In the case of the modified area “B,” the average value was 116 N. Peel-off results of both samples give similar average adhesion strength results. Additionally, in the case of the modified area, it was observed that the nature of tearing is more uniform – the amplitude of forces is smaller than in the case of a sample torn off in the area without modification. In the case of modification, adhesion is influenced both by surface development and by changes in the substrate material to which the EVA copolymer film is laminated.

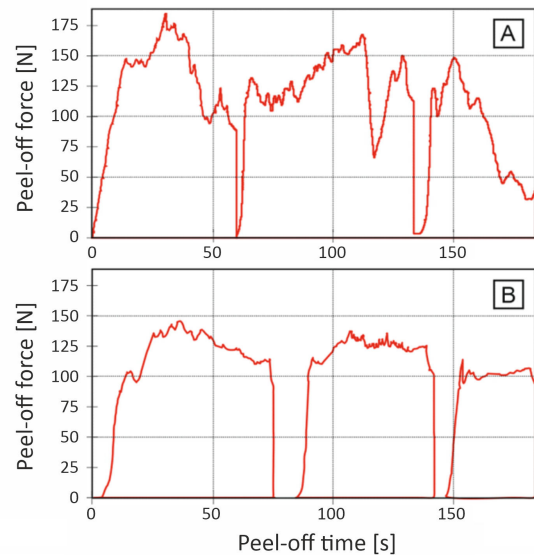


Fig. 4. Peel-off force vs. peel-off duration for a non-modified structure “A” and a modified structure “B”.

Finally, the PV module corrosion resistance was checked by measuring and comparing the PV module series resistance which is subject to damp-heat (DH) conditions. The experiment was designed so that two PV modules of  $1160 \times 550 \text{ mm}^2$  each in the glass-glass arrangement were prepared. One module was prepared without any modifications, serving as a reference, while the second module was modified in the way that 2 mm wide strips were produced in all inter-cell gaps, as well as around the perimeter of the module near the cells. The modification was a two-step laser process: CO<sub>2</sub> laser engraving followed by zinc coating using the LIBT technique, using the same parameters as for EVA cross-linking degree and adhesion measurement. Implementation areas are marked in Fig. 5.

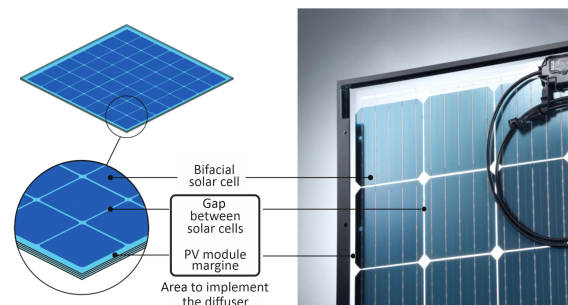


Fig. 5. Implementation areas for the proposed modification.

Both modules were then subject to DH burden. After initial  $I$ - $V$  parametrization, the modules were placed in a chamber at 85 °C, with a relative humidity of 85% for 1000 h. After that, the  $I$ - $V$  measurements were performed again and compared with initial results as shown in Table 2.

The data presented in Table 2 indicate that the majority of electrical parameters of the tested modules exhibit comparable values for both the unmodified system and the system in which the modification described in this article was implemented. However, differences are observed in the  $R_s$  values and the  $I$ - $V$  characteristics related to  $FF$ .

**Table 2.**

*I-V* measurement results before and after DH burden for reference and modified PV modules.

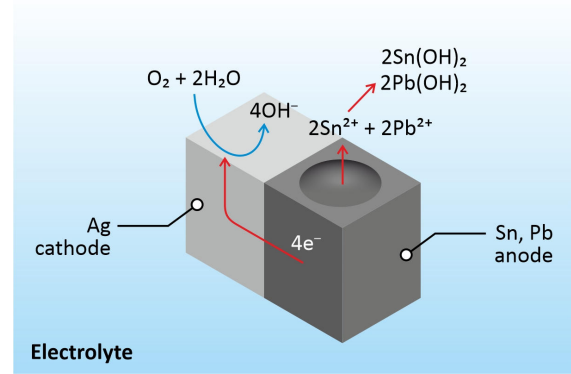
Parameter	Reference module initial	Reference module after DH	Modified module initial	Modified module after DH
$V_{oc}$ [V]	10.302	10.276	10.285	10.195
$I_{sc}$ [A]	8.787	8.863	8.351	8.435
$V_{mpp}$ [V]	8.161	8.173	8.317	8.269
$I_{mpp}$ [A]	8.386	8.355	8.024	8.019
$P_{max}$ [W]	68.44	68.287	66.738	66.312
$FF$ [%]	<b>75.6</b>	<b>74.98</b>	<b>77.7</b>	<b>77.11</b>
Cell Eff [%]	18.69	18.65	18.23	18.11
Mod Eff [%]	12.57	12.54	12.26	12.18
$R_s$ [mΩ]	<b>193.09</b>	<b>203.18</b>	<b>188.15</b>	<b>188.37</b>
$I_{op}$ [A] at 9.00 V	6.684	6.402	6.757	6.44

For the reference module (unmodified), the  $R_s$  values before and after the DH test were 193.09 mΩ and 203.18 mΩ, respectively. In contrast, for the module in which the zinc selective light diffuser was applied, the  $R_s$  values were 188.15 mΩ before DH test and 188.37 mΩ after DH test. It is important to note not only the lower  $R_s$  value in the modified module, but also that in this case no increase in  $R_s$  was observed after the DH test. Similarly, the  $FF$  is lower (worse) for the unmodified module, with a value of 75.6 and further deteriorates (decreases) after the DH test.

Degradation mechanism of metallization involves corrosion. Chemical, physical or electrochemical reactions can cause the corrosion. The corrosion of metals typically proceeds as an electrochemical reaction, since electrons can migrate in the metal and ions can be released into the environment. An aqueous environment is necessary for the electrochemical corrosion of metals to allow ion conduction or gas-metal reactions to be possible at high temperatures. During the production of PV modules, Cu wire is plated with SnPb solder, resulting in the creation of six galvanic couples within the PV module: Ag–Pb, Ag–Sn, Cu–Pb, Cu–Sn, Ag–Cu, and Sn–Pb. The oxidation potentials in descending order are as follows: Ag/Ag(I): +0.799V, Cu/Cu(II): +0.337V, Pb/Pb(II): –0.126V and Sn/Sn(II): –0.136V. An electric circuit is closed with an encapsulation polymer which plays the role of an electrolyte. Aging of the EVA encapsulating material may accelerate the metallization corrosion due to the degradation by-product – acetic acid [17], which may lead to the metallization corrosion [18, 19]. Water ingress facilitates the delamination of EVA from the cell [16, 20] and, thus, the grid corrosion.

Metals with lower potential values oxidate (corrode) more willingly than metals with higher potential values. Accordingly, Sn and Pb materials become the anode and tend to corrode at an accelerated rate, whereas Ag and Cu materials act as the cathode.

Therefore, when added to the corrosion cell system, a metal with a lower potential value than both Sn and Pb will act as the anode and tend to corrode. The oxidation potential value for Zn/Zn(II) is –0.763 V. Zn corrodes at a greater rate than Sn and Pb when added to the PV solder



**Fig. 6.** Corrosion mechanism at the interface between SnPb solder and Ag.

system, as shown in Fig. 6. Zn then can play the role of a sacrificial structure.  $R_s$  of the module can be monitored to see if it has increased due to poor contacts resulting from corrosion.

#### 4. Conclusions

First, the proposed metal structure fully integrated with the PV module does not influence major reliability parameters. Second, the presence of modification does not influence the degree of EVA cross-linking. The adhesion of the modified surface is not influenced if compared to the surface without any modification. These two experiments prove that the PV module reliability remains intact compared to the standard module. It may be concluded that lamination quality remains optimal and uniform across the modified PV module area. Finally, the DH test results show that the structure may prevent module degradation from increasing series resistance. The corrosion of solder/silver connections poses serious difficulties for outdoor-exposed PV modules, as connection degradation contributes to the increase in  $R_s$  of the PV modules. The modified module maintains its initial  $R_s$ , while the module without modification is affected by a 5% increase in  $R_s$ .

The main research thread presented in this work is the effect of the presence of a diffuser and, in particular, a zinc layer, on the reliability of the PV cell. The work also presents the positive effect of the produced diffuser on the electrical parameters of the PV cell. Especially, the correctly aligned structure may increase the efficiency of the PV module by up to 2%. The authors' research has shown that an integrated zinc-based structure may act as anodic protection to the solder/silver connection, being the least noble sacrificial metal that mitigates corrosion. Based on the obtained results, the authors can conclude that the sacrificial metal may improve the long-term reliability of PV modules under DH conditions.

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## References

- [1] Solar Power Europe. Global Market Outlook for Solar Power 2022–2026 (2022). <https://www.solarpowereurope.org/insights/market-outlooks/>
- [2] International Energy Agency (IEA). Renewables 2020, Analysis and forecast to 2025 (2020). <https://www.iea.org/reports/renewables-2020>
- [3] Shell International. The energy transformation scenarios (2021). [www.shell.com/transformationsscenarios](http://www.shell.com/transformationsscenarios)
- [4] Ajayan, J. et al. A review of photovoltaic performance of organic/inorganic solar cells for future renewable and sustainable energy technologies. *Superlattices Microstruct.* **143**, 106549 (2020). <https://doi.org/10.1016/j.spmi.2020.106549>
- [5] German Mechanical Engineering Industry Association (VDMA). International Technology Roadmap for Photovoltaic (ITRPV), 14th Edition (2023). <https://www.vdma.org/international-technology-roadmap-photovoltaic>
- [6] Kuhn, T. E. et al. Review of technological design options for building integrated photovoltaics (BIPV). *Energy Build.* **231**, 110381 (2021). <https://doi.org/10.1016/j.enbuild.2020.110381>
- [7] Gholami, H., Røstvik, H. N. & Steemers, K. The contribution of building-integrated photovoltaics (BIPV) to the concept of nearly zero-energy cities in Europe: Potential and challenges ahead. *Energies* **14**, 6015 (2021). <https://doi.org/10.3390/en14196015>
- [8] Barbusiński, K. et al. Influence of environmental conditions on the electrical parameters of side connectors in glass–glass photovoltaic modules. *Energies* **17**, 680 (2024). <https://doi.org/10.3390/en17030680>
- [9] Kwaśnicki, P. et al. Characterization of the TCO layer on a glass surface for PV II<sup>nd</sup> and III<sup>rd</sup> generation applications. *Energies* **17**, 3122 (2024). <https://doi.org/10.3390/en17133122>
- [10] Jeremiasz, O. et al. Laser modified glass for high-performance photovoltaic module. *Energies* **15**, 6742 (2022). <https://doi.org/10.3390/en15186742>
- [11] Drabczyk, K., Sobik, P., Kulesza-Matlak, G. & Jeremiasz, O. Laser-induced backward transfer of light reflecting zinc patterns on glass for high performance photovoltaic modules. *Materials* **16**, 7538 (2023). <https://doi.org/10.3390/ma16247538>
- [12] Kim, J.-H., Park, J., Kim, D. & Park, N. Study on mitigation method of solder corrosion for crystalline silicon photovoltaic modules. *Int. J. Photoenergy* **2014**, 809075 (2014). <https://doi.org/10.1155/2014/809075>
- [13] Kyranaki, N. et al. Damp-heat induced degradation in photovoltaic modules manufactured with passivated emitter and rear contact solar cells. *Prog. Photovolt.* **30**, 1061–1071 (2022). <https://doi.org/10.1002/pip.3556>
- [14] Segbefia, O. K., Akhtar, N. & Sætre, T. O. Moisture induced degradation in field-aged multicrystalline silicon photovoltaic modules. *Sol. Energy Mater. Sol. Cells* **258**, 112407 (2023). <https://doi.org/10.1016/j.solmat.2023.112407>
- [15] Miller, D. et al. Examination of a Standardized Test for Evaluating the Degree of Cure of EVA Encapsulation. in *2013 Photovoltaic Science and Engineering Conference (Asian PVSEC)* 1–19 (NREL, 2013).
- [16] ASTM International. ASTM D2765-16 (ISO 10147, Method B): Standard Test Methods for Determination of Gel Content and Swell Ratio of Crosslinked Ethylene Plastics. <https://www.astm.org/d2765-16.html>
- [17] Ketola, B. & Norris, A. Degradation Mechanism Investigation of Extended Damp Heat Aged PV Modules. in *Proc. of the 26<sup>th</sup> European Photovoltaic Solar Energy Conference (EUPVSEC)* 3523–3528 (PVSEC, 2011).
- [18] Czanderna, A. W. & Pern, F. J. Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review. *Sol. Energy Mater. Sol. Cells* **43**, 101–181 (1996). [https://doi.org/10.1016/0927-0248\(95\)00150-6](https://doi.org/10.1016/0927-0248(95)00150-6)
- [19] Kempe, M. D. et al. Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices. *Sol. Energy Mater. Sol. Cells* **91**, 315–329 (2007). <https://doi.org/10.1016/j.solmat.2006.10.009>
- [20] Quintana, M. A., King, D. L., McMahon, T. J. & Osterwald, C. R. Commonly Observed Degradation in Field-Aged Photovoltaic Modules. in *Conference Record of the 29th IEEE Photovoltaic Specialists Conference* 1436–1439 (IEEE, 2002).