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Article

Polyethylene Protective Coating with Anti-Reflective Properties for Silicon Photovoltaic Cells

Malgorzata Pociask-Bialy [1,*]

[1] College of Natural Sciences, University of Rzeszów, Pigonia 1 Str., 35-959 Rzeszów, Poland
* Correspondence: mpociask@ur.edu.pl

Abstract: The aim of the study was to find the effect of polyethylene (PE) coatings on the short-circuit current of silicon photovoltaic cells covered with glass, in order to improve the short-circuit current of the cells. Various combinations of PE films (thicknesses ranging from 9 to 23 μm, number of layers ranging from 2 to 6) with glasses (greenhouse, float, optiwhite and acrylic glass) were investigated. The best current gain of 4.05% was achieved for the coating combining a 1.5 mm-thick acrylic glass with 2 × 12 μm-thick PE films. This effect can be related to the formation of an array of micro-wrinkles and micrometer-sized air bubbles with a diameter of 50 to 600 μm in the films, which serve as micro-lenses and enhance light trapping.

Keywords: photovoltaic cells; antireflective coatings; solar glass transmittance; short-circuit current gain

1. Introduction

Research on the use of polyethylene (PE) as a material for protective and anti-reflective (AR) coatings in photovoltaics (PV) has been conducted for a long time, but intensified in the recent years [1–3]. A simple method to fabricate moth-eye-like AR nanostructures n ion- beam etching onto polymer was presented in paper [4]. PE multilayer coatings can be used as an alternative to heavy glasses, as light transmittance of these coatings was proven to be equal to that of high-quality solar glasses, amounting to 85–90%. Patterning and/or fabrication of small topological features in the coatings help to increase light trapping [5,6]. For example, increase in energy efficiency of 1.34% for silicon modules with millimeter-sized cylindrical lenses obtained with a delicate embossing technique on an epoxy resin-based polymer (ERP) was as much as 10% for exposure with incidence angles ranging from 0 to 60^0 [7]. The authors of Ref. [8] presented a hybrid concept where flat high-performance multi-junction solar cells made of III-V materials were mounted on the rear surface of concentrating PV solar modules. The results of external tests with two different designs of hybrid modules showed an absolute increase in the average daily efficiency ranging from 1.02% to 8.45%, depending on the weather conditions [8].

The authors of Ref. [9] proposed a theoretical hybrid structure improving the efficiency of crystalline silicon solar cells: ordered nanoporous silicon (np-Si) with polythiophene (PT) filling inside the pores. This structure showed a significantly increased absorption coefficient as compared to 'pure' np-Si, proving np-Si/PT heterojunction to be a better light absorbing material. The polymer that filled the pores produced a highly scattered valence band that was the main route for hole transport. The Si/PT structure efficiently dissociates photo-induced electron-hole pairs and reduces the amount of material required for light absorption, leading to the fabrication of inexpensive yet highly efficient solar cell with an efficiency of 30% for a material thickness of just 5 μm [9].

The authors of Refs. [10,11] confirmed that fillings or encapsulants may play a big role in PV cell efficiency, and that the physical properties of the materials used are very important. For example, the use of polyolefin elastomer (POE) or thermoplastic polyolefin (TPO) [10] instead of ethylene vinyl acetate (EVA) encapsulant in PV cells allowed for extending the spectral range to 250 - 400 nm range (ultraviolet, UV range), which compensated for the low transmittance in the visible range. TPO

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showed a degree of crystallization three times higher than EVA, and with POE it was twice as high as with EVA [10].

Increasing the efficiency of the cell, which is the subject of the research presented in this work, can be obtained by selecting an appropriate glass with high transmittance, close to 90%, and by the use of micro-concentrators (such as micrometer-sized lenses and/or sub-millimeter topological features [11]) with the functionality of an AR layer. In this paper, we present the results of the study of the effect of 'micro-structuring' of the PE coatings, achieved via formation of an array of micro air lenses with a diameter of 50 to 600 μm and micro-wrinkles enclosed between several layers of PE film, on the short-circuit current of silicon PV cells covered with glass.

2. Materials and Methods

The experiments were performed on the basis of Sec 4.4W 3bb crystalline silicon cell certified by the Fraunhofer Institute (ISE CalLab Cells, Fraunhofer, ISE, Freiburg Germany Multicrystalline silicon, Certificate Nr: 47058-PTB-12) with the following parameters: dimensions, 15.6 × 15.6 cm; short-circuit current I_{sc}, 9.01903 A; maximum current I_{max}, 8.46612 A; open circuit voltage U_{oc}, 0.639647 V; maximum voltage U_{max}, 0.5355 V; maximum power point MPP, 4.5336 W; fill factor FF, 78.5857 %, efficiency η, 18.6292 %. The cell was covered with various commercially available (szklonawymiar.pl) glasses: greenhouse glass, float glass, optiwhite glass and acrylic glass (plexiglass).

Tested were two groups of glass types, totaling 10 samples. These included: i) 10 cm × 10 cm glass samples: 2 pieces of 2 mm-thick float glass, 2 pieces of 4 mm-thick float glass, 2 pieces of 4 mm-thick greenhouse glass, and 1 piece of optiwhite glass; and ii), 16 cm × 16 cm glass samples: 1 piece of 1.5 mm-thick acrylic glass (plexiglass), 1 piece of float glass and 1 piece of greenhouse glass, both 4 mm-thick. As a result of determining the transmittance T of these samples on the basis of the current-voltage characteristics of the TSec4 cell covered with selected samples (Figure 1), three glass samples were selected with the highest transmittance. These were 2 mm-thick float glass (T_{Float}=89.6%), 4 mm-thick optiwhite glass ($T_{Optiwhite}$=90.0%,), and 1.5 mm-thick acrylic glass (T_{Plexi}=92.5%). The accuracy of determining the transmittance with this method was about 0.2%. The transmittance measurements were performed using the AAA+ Quick Sun QS130CA solar radiation simulator (Endeas Oy, Finland) [12] at Standard Tests Conditions (STC: 1000 W/m^2, 25 °C, AM1.5G).

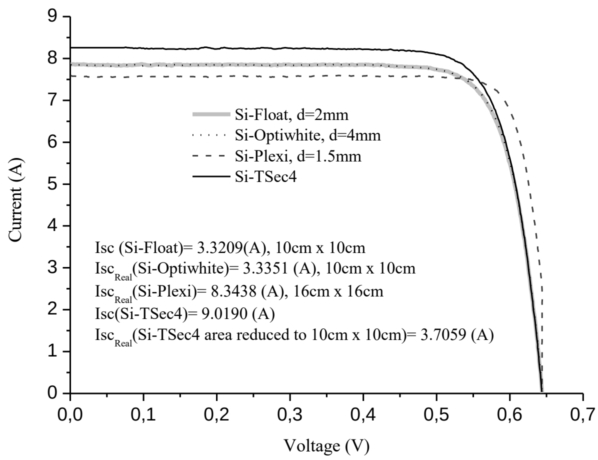

Figure 1. Current-voltage characteristics of PV cells covered with glasses used for the determination of the transmittance of the glasses with the use of QS130CA solar radiation simulator.

The photoconversion efficiency was determined on the basis of the standard method [13], which analyzes the change in I_{SC} of the covered cell with respect to I_{SC} of the 'bare' silicon cell.

The transmittance of the glasses in the wavelength range 175 - 3500 nm was double-checked using the CARY5000 spectrometer, these data are shown in Figure 2. At 555 nm wavelength, the obtained values were: $^*T_{Float}$ = 91.07%, $^*T_{Optiwhite}$= 90.70%, $^*T_{Plexi}$= 92.16%. The accuracy of transmittance measurements was about 0.05%. The transmittances of the glasses determined with two methods appeared to be very similar.

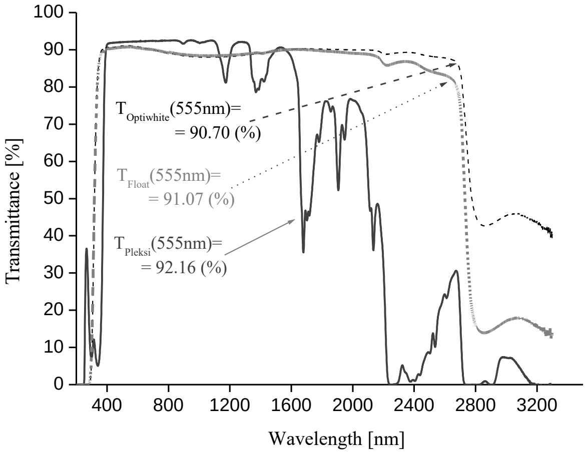

Figure 2. Transmittance of selected glasses determined with the use of CARY5000 integrating sphere spectrophotometer.

Other glass samples, including float glass with a thickness of 4 mm and greenhouse glass, showed photoconversion efficiency below 85% and were excluded from further consideration.

3. Results

Fifty seven (57) types of coatings were made with 2, 4, or 6 layers of PE films with thickness 9, 12 or 23 µm on 10 × 10 cm glass samples (float and optiwhite glass) and 16 cm × 16 cm acrylic glass samples. The density of the PE films was 0.918–0.920 g/cm^3. Each PE film covered just 41% of the crystalline silicon cell, so the rest of the cell was exposed and the short-circuit current component from the exposed part of the cell was subtracted from the value of the total I_{sc} registered with the QS130CA simulator. The films were commercially available (dobrafolia.pl, bifol.pl, etc.) PE films, and they were applied by hand ensuring that there were no traces of material tension in the form of excessively large wrinkles, which was checked with an optical microscope. On the other hand, smaller-sized wrinkles help to enclose air bubbles between the glass and films, and these bubbles serve as micro air lenses. Three types of typical wrinkle widths were observed: D1 with the 'width' (diameter) less than 50 µm; D2, with the diameter 50-600 µm; and D3, with the diameter 600-1200 µm. Also, two types of wrinkle length were observed: L1 with the length of several millimeters, and L2 with the length of several centimeters. Each system was prepared anew 3 or 4 times, until the width ('diameter') of the wrinkles did not exceed 600 µm and surface density of the wrinkles, 15%. Wrinkle density was calculated for 5-7 averaged randomly selected fields sized 2.5 × 2.5 mm.

Based on the current-voltage characteristics such as shown in Figure 3 for acrylic glass, the photoconversion efficiency of the cells covered with the studied 'glass-PE films' structures were determined, and the data obtained are summarized in Table 1.

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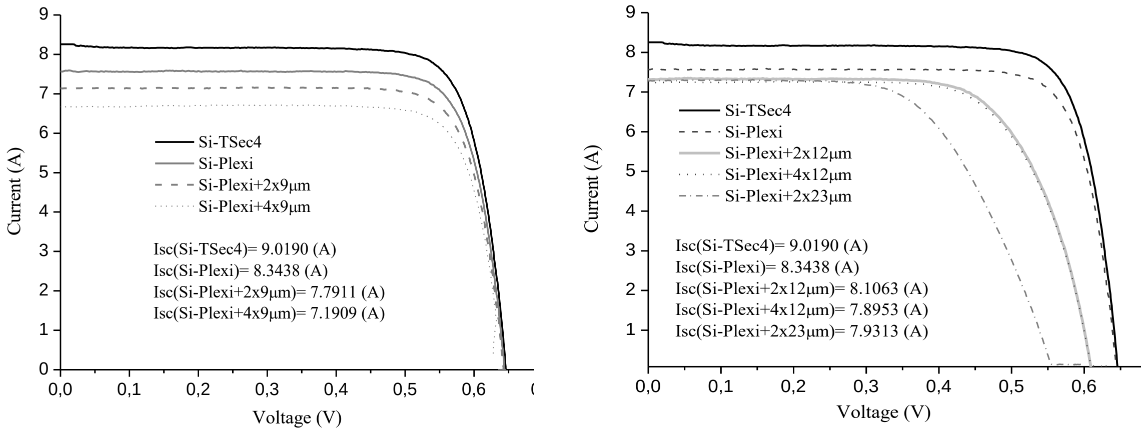

(**a**) (**b**)

Figure 3. Current-voltage characteristics of PV cells covered with 'acrylic glass-PE film' structures with 9 μm-thick PE films (**a**) and with 12 μm- and 23 μm-thick films (**b**), used for the determination of photoconversion efficiency of the cells.

Table 1. Photoconversion efficiency of the studied systems, determined with the Solar Radiation Simulator QS130CA.

Studied object	PE film thickness, μm	I_{sc}, A	Efficiency of photoconversion, %	I_{sc} gain, %
Float glass, *d*=2 mm, 10 ×10 cm	Pure glass	8.6340	89.61	
	2 × 9	8.4917	85.77	RC
	4 × 9	8.3656	82.37	
	6 × 9	8.1033	75.29	
	2 × 12	8.4937	85.82	0.06
	4 × 12	8.2426	79.05	
Optiwhite glass, *d*=4 mm, 10 × 10 cm	Pure glass	8.6483	90.00	
	2 × 9	8.4909	85.75	RC
	4 × 9	8.2787	80.02	
	6 × 9	7.8965	69.71	
	2 × 12	8.4664	85.82	0.09
	4 × 12	8.2679	79.05	
	2 × 23	8.2352	78.85	
	4 × 23	7.9551	71.29	
Acrylic glass, *d*=1.5 mm, 16 × 16 cm	Pure glass	8.3438	92.51	
	2 × 9	7.7911	86.38	
	4 × 9	7.1909	79.73	
	6 × 9	6.7526	74.87	
	2 × 12	8.1063	89.88	4.05
	4 × 12	7.8953	87.54	1.34
	2 × 23	7.9313	87.94	1.80
	4 × 23	7.0493	78.16	

In this Table, column 1 lists the object, for which the photoconversion efficiency was determined; *d* is the thickness of the glass, and the size of the glass sample is also given. PE films were applied to the glass on both sides. Column 2 shows the value of I_{sc} measured experimentally, the values obtained were reduced to the area of the samples, so the comparison of the results obtained on different samples was correct. The systems with the simplest coatings, 2 × 9 μm-thick films, were chosen as a 'reference coating' (RC), and the value of the current gain was calculated for the remaining films against the I_{SC} of these coatings. The final column in Table 1 shows the I_{SC} gain, the accuracy of determination of the gain was 0.02%. For the samples where no gain was achieved, the cells in this column were left empty.

On the basis of the analysis of the data in Table 1, it can be observed that the most substantial I_{sc} gain was achieved for 1.5 mm-thick acrylic glass; in relation to RC it was:

1. with two layers of 12 µm-thick PE films - 4.05%,
2. with two layers of 23 µm-thick PE films - 1.8%, and
3. with four layers of 12 µm-thick films - 1.34%.

The 2 mm-thick float glass with two 12 µm-thick PE films showed a current gain of only 0.06%, and the optiwhite glass showed a gain of 0.09% for the glass with two 12 µm-thick films.

Thus, the system with acrylic glass and two layers of PE film with a thickness of 12 µm each appeared to be the most effective coating for the PV cells.

4. Discussion

During the application and slight stretching of the film (performed just for good adherence to the smooth, non-structured surface of the glass), air bubbles with diameters 50 - 600 µm were formed, as discussed above. While the nominal thickness of a 1.5 mm-thick glass with two layers of 12 µm-thick PE films should equal 1.524 mm, the thickness of the PE layer was actually increased by the height of the wrinkles and air bubbles to the values ranging from 1.550 mm to 1.850 mm, as was determined using a digital optical microscope with a magnification of ×50 with the accuracy of the determination of the thickness Δd=0.002 mm. The resulting structure with the wrinkles and the bubbles resembles a well-known 'grooves'-like glass texture, which is used for enhancing the PV modules performance. A good example of this texture was presented by the authors of Ref. [14]. The similarity between this texture and the structure formed in our samples is especially close in the case of cross-overlapping of successively applied PE films.

The 'grooves'-like texture is effective for the angles of incidence of solar radiation in the range of 55-80°; at these angles it shows an open current gain of as much as 60%, while for normal incidence, only 1.4 % of the gain is obtained for the same structure [14] (see Figure 4, dark bars).

To compare the results obtained in this work with those obtained for the 'grooves'-like texture, we performed simulations for our most effective system (acrylic glass with two layers of 12 µm-thick PE film). In the simulations, the nature of I_{SC} gain amplification was assumed to be similar to that presented in Ref. [14]. The dependence of the gain on the incidence angle was described by a polynomial of the fifth order:

$$y = 4{\cdot}10^{-7}x^5 - 7{\cdot}10^{-5}x^4 + 4{\cdot}10^{-3}x^3 - 0.097\,x^2 + 0.777\,x + 1.099, \qquad (1)$$

where x is the angle, y is the I_{SC} gain, and the initial condition for the normal angle of incidence is that the I_{SC} gain is equal to 1.4 % (indicated by black bars in Figure 4).

In modeling this process for I_{SC} gain (0°) = 4.05 % presented here (white bars in Figure 4) a nearly 50% reduction in final I_{SC} gain as a function of incident angle was accounted for. These losses are primarily due to scattering of solar radiation on film wrinkles and air lenses with sizes smaller than 25% of their maximum size. Comparing the properties of the two coatings shown in Figure 4, we find that despite the significant theoretically assumed reduction in I_{SC} gain for the system of acrylic glass and two layers of 12 µm-thick PE films, in reality its capabilities appear to be at least 30% greater than for 'grooves'-like textured glass.

The results obtained in the present research are indicative of the fact that a high value of the current gain for acrylic glass coated with PE films can be achieved. Acrylic glass, or plexiglass, belongs to the same group of materials as PE films; it has exactly the same heat transfer coefficient. In addition, it had the highest transmittance of all glasses studied. So, the best results obtained for this type of glass can be explained by the fact that when applying PE films to acrylic glass, we dealt with the same family/group of polymeric materials. For the best configuration found in this work, a gain of ~4% was achieved, and for incidence angles in the range of 70-80° it should certainly be much greater than 4%, possibly even more than 60% reported by authors of Ref. [14] for 'grooves'-textured glass.

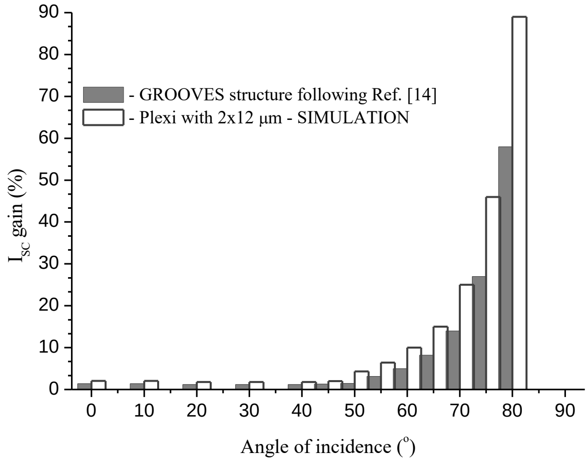

Figure 4. Relative I_{SC} gain as a function of angle of incidence for 'grooves'-like texture presented in Ref. [14] (dark bars) and the results of simulation for acrylic glass with two 12 μm-thick PE films (white bars).

The obtained results are in good agreement with reports on the use of a 30 μm-thick PE layer for improved long-term durability but with significant loss in efficiency of crystalline silicon cells enclosed EVA, over which a single PE layer has been placed [15]. The method of improving the efficiency of silicon cells described in Ref. [9] could also be applied to PE films, and the use of a different encapsulant should extend the spectral range of solar radiation converted into electricity in the modules modified by the addition of PE films.

In regards to future research directions, we may also suggest that further efficiency enhancement may be achieved by using specialized glasses, such as a low-iron AR-nanostructured glass manufactured by Effect Glass [16]. The improvement of the efficiency of PV elements covered with this glass in the spectral range of 700 - 800 nm at the incidence angles 70 - 80^0 was reported to be of the order of at least 3% [13]. In our own research [17], an I_{sc} gain of 2% was obtained for a textured glass with an AR layer. In the experiments discussed in Ref. [17], a sample of unstructured glass measuring 10 × 10 cm and with thickness 3.2 mm showed the transmittance (as determined with the use of QS130CA with the same TSec4 reference cell as the one used in this work) equal to 82.26%. In this work, the best coating consisting of acrylic glass with 2 × 12 μm-thick PE films showed a transmittance of 86.38%. Therefore, using the specialized AR glass clearly should enhance the short-circuit current even more. Optimizing 'glass-PE' configuration and fabricating mechanically robust composite glass-polymer system should allow for further improving the photoconversion capabilities of silicon PV modules.

5. Conclusions

In this paper, we studied the effect of various PE coatings on the short-circuit current of silicon PV cells covered with different types of glasses. The best current enhancement of 4.05% was achieved for the coating consisting of a 1.5 mm-thick acrylic glass with 2 × 12 μm-thick PE films.

It is believed that this effect is due to the formation of an array of micro air lenses with an average diameter of 50 to 600 μm and micro-wrinkles enclosed between the layers of the film and at the film/glass interface.

The incorporation of a stable, non-defatable when enclosed, system of two polyethylene foils between which air bubbles are trapped acting as micro-concentrators, and placing them in EVA between a typical 3 mm thick optiwhite tempered glass and a silicon photovoltaic cell, i.e. manufacturing a prototype of a photovoltaic module, confirmed the effect of short-circuit current gain about several (4 to 6) percent. Mentioned results are the subject of unpublished author's research [18]. Moreover, aging with UV light only slightly reduces the performance of such a crystalline silicon module prototype in comparison with [15]. The similar result was achieved at paper [19], where efficient light trapping in vertically aligned n-type and p-type 2D random (interconnected pores) array of Si-NWs have been reported, and antireflection properties of these synthesized Si-NWs shows maximum light trapping because of high density of NWs. The power cell efficiency of Si-NWs exhibited about 4%, but technological requirements and research costs were many times higher than those presented in this paper. Study of light trapping in polyethylene protective coating with anti-reflective properties for silicon photovoltaic cells have been explored to add new dimension in the field of photovoltaic application.

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Data Availability Statement: The data presented in this study are available on request from the author.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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