BLACK, INFRARED REFLECTING BACKSHEETS FOR PV: WHERE AESTHETICS MEETS PERFORMANCE

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ABSTRACT: To reduce cell-to-module (CtM) losses for aesthetically appreciated all-black modules we applied a black powder coating with low infrared absorption to standard back foils used in PV modules. Upon the application of such powder coating the IR reflective properties of the underlying substrate are largely preserved. For Cu foil substrates approximately 85% reflection in near-infrared was recorded, while for a white polyamide substrate reflection was 60%. These black, IR reflecting back foils were incorporated in single-cell laminates with n-Pasha bifacial solar cells. From these structures the potential I_{sc} gain from the application of such coatings in PV modules as compared to conventional all-black modules is estimated to be 1.4 – 1.8%.
Keywords: PV module, Backsheet, Bifacial, Light Trapping, Ray Tracing

1 INTRODUCTION

The large-scale deployment of photovoltaics, in particular in the built environment, raises the importance of the aesthetics of PV modules. In this respect, the PV product portfolio is being diversified with products with different appearances and functionality. Examples of this are modules with colored cells, PV roof tiles and façade elements which should take over the functionality of conventional building elements facilitating building-integrated PV (BIPV). Currently, all-black modules are widely available and highly appreciated both for building-integrated and building-applied applications. To ensure a black appearance these modules are manufactured with a black backsheet.

In contrast, standard crystalline silicon modules incorporate a white reflective backsheet. The backsheet in the PV module is both a barrier to moist and ultraviolet (UV) radiation and acts as an electrical insulator. At the same time the use of a reflective foil as backsheet improves the output of a PV module through (diffuse) reflection of the light that falls on it. Part of the light that impinges on the exposed backsheet area in between the cells and along the outer edge of the module is re-directed towards the cells after reflection and trapping at the glass-air interface. The contribution of the light reflected from the backsheet to the output power of a PV module depends on its reflectivity and the spacing of the cells but can easily be in the range of 2 – 3% [1]. In addition, when bifacial cells are used the infrared (IR) light transmitted by the cell will be efficiently reflected from the area behind the cell, improving the IR response of the module. In the case of all-black modules the use of a black, absorbing back foil adds to the aesthetics of the module, however this comes at the price of a lower power output.

In the built environment innovative coatings are being applied to reduce the temperature of objects, such as roofs and façade elements. The application of such coatings lowers the need for air-conditioning. These coatings are available in multiple colors and black and can be applied in an electrostatic powder-coating process. To realize the cooling effect the coatings should have very limited absorption in the IR. To our opinion such coatings are of great interest for application in all-black PV modules. The combination of black, low IR absorption powder coatings with highly reflective back foils would reduce the inherent losses in all-black modules associated with the use of absorbing backsheets. Figure 1 illustrates the differences in module light management for an absorbing and reflecting (black) backsheet.

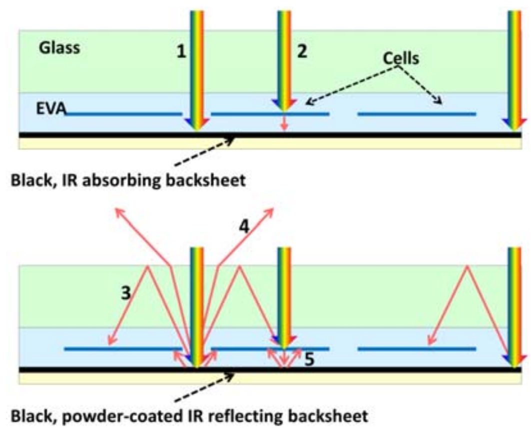

Figure 1: Illustration of the improved module light management in case of a black, IR reflecting backsheet. 1) Incident radiation absorbed by backsheet, 2) Transmitted (IR) radiation absorbed by backsheet, 3) IR part of incident radiation reflected and trapped at front, 4) As 3) but within escape cone, 5) Transmitted radiation reflected and re-entering cell through rear.

In addition, the reduced IR absorption (and IR transparency) of the black, powder coated (BPC) foils compared to conventional, absorbing black foils is thought to result in lower operating temperatures for all-black modules, which should further enhance their performance under operation conditions.

Here, we investigate the use of a black, powder coating (Alesta® Cool by Axalta) with low absorption in the IR spectral range to generate visually black but IR reflecting backsheets. For this purpose we have applied the coating to standard reflecting PV back foils, namely white polyamide and copper foil. In this study, we have focused on its effects on module light management, which we study both experimentally and in ray-tracing simulations.

2 METHODOLOGY

2.1 Experimental

Alesta® Cool, a polyester based, black powder

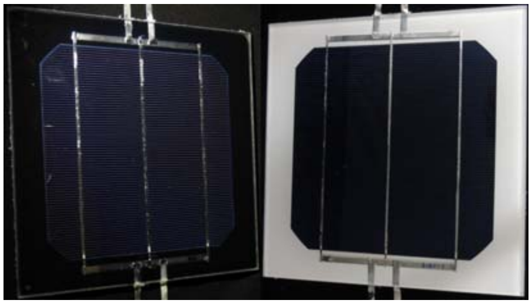

Figure 2: Images of single-cell laminates prepared with either white polyamide or black-powder coated polyamide.

coating from Axalta, was applied to standard white polyamide and Cu foils in an electrostatic spray-coating process. The powder coating was applied by a specialized company, Eurolacke B.V. Reflection measurements of the different backsheet materials were performed on a homebuilt spectrophotometer set-up which includes an integrating sphere.

Three busbar, bifacial n-Pasha cells [2] from previous baseline experiments were selected for this study. IV-characteristics of these cells were measured on a Wacom class AAA solar simulator with a brass reflective chuck. The cells were measured from front and rear to determine the bifaciality factor. From these measurements cells with very similar performances were selected for fabrication of single-cell laminates. The front-measured parameters amounted to an I_{sc} of 9.18 ± 0.02A (average ± standard deviation) and a conversion efficiency of 19.67 ± 0.09%. The rear I_{sc} and efficiency were 8.04 ± 0.07A and 17.2 ± 0.2% respectively. The bifaciality factor of this set of cells was 87%. The cells were distributed randomly over 4 groups, which showed no significant difference in performance against each other.

The selected cells were encapsulated in a 20 cm × 20 cm glass – EVA – backsheet stack. The thickness of the glass used was 3 mm, while front and rear EVA were both 450-μm thick. The black reference laminates incorporated a black absorbing backsheet. In Figure 1 images of laminates fabricated with white polyamide and black powder coated polyamide are included.

All laminates were measured under STC in a room with black walls with a Pasan module flash-tester, class AAA Different masks were applied to the laminates in these measurements to vary the exposed area of the backsheet surrounding the cells. With the masks used aperture areas of 0, 3, 5, 10 and 22 mm around and including the cell were realized.

2.2 Ray tracing simulations

With our homebuilt ray-tracing software [3] a simple model structure of the single-cell laminates was defined to simulate the trend in the I_{sc} measurements as function of the aperture size. The model includes the module optical stack but no detailed optical model of the solar cell was included. Instead, it was assumed that each ray interacting with the solar cell is absorbed. Simulation runs with varying aperture widths were performed for the different backsheets used in the experiments in the 330 – 1100 nm wavelength range. The reflection parameters for the different backsheet materials were derived from experiments. No change in refractive index was assumed between EVA and the respective backsheets. The

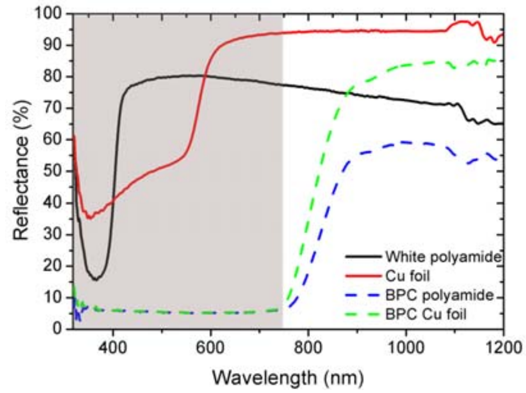

Figure 3: Reflectance data of the standard and BPC polyamide and Cu foils used in this study.

backsheet reflection was considered to be fully Lambertian. The simulation results were normalized on the measured I_{sc} values for 0 mm aperture.

3 RESULTS

The reflectance of samples of white polyamide and Cu foil were measured together with similar samples which had received the black, powder coating. The results are included in Figure 3. It is apparent that the application of the coating results in full absorption of all light in the UV and visible (VIS) range. It appears therefore, truly black to the human eye. Above 750 nm the absorption rapidly decreases. The coating becomes more and more transparent in this spectral range which is observed as an increasing reflection in Figure 3 for the coating-substrate systems considered here. When applied to a glass substrate extensive transmission is seen in this spectral range (data not shown). From the reflection and transmission data for the polyamide foils (polyamide is slightly transparent in the VIS to near-infrared (NIR) range) we find that the powder coating absorbs on the order of 10 - 15% of the incident light in the NIR range in the configurations considered here. For the BPC polyamide this amounts to a reflection of around 60% in the NIR spectral range while for BPC Cu foil reflection is as high as 85%. In addition, to the total reflectance also diffuse reflectance only spectra were recorded. It was found that the addition of the BPC did not significantly affect the ratio diffuse-to-total reflection. This ratio was at least 93% for all materials.

We performed an analysis of how the different backsheet materials affected the I_{sc} of the single-cell laminates. In Figures 4A and B the results are summarized for two cases: A) the laminates were masked to illuminate the cell area only and B) the full laminates including their 22 mm edge areas were illuminated. In addition to the copper and polyamide based backsheets also conventional black laminates were included. This latter laminates included n-Pasha cells from a different baseline run with a slightly higher efficiency and higher bifaciality factor In order, to compare them to the laminates discussed here a scaling factor was applied. This scaling factor was derived from a comparison of single-cell laminates of white polyamide and Cu foil which were fabricated for both sets of cells. Case A corresponds to the situation in which the backsheets will interact with light transmitted by the solar cell only. Since, we have used bifacial cells in this study part of the

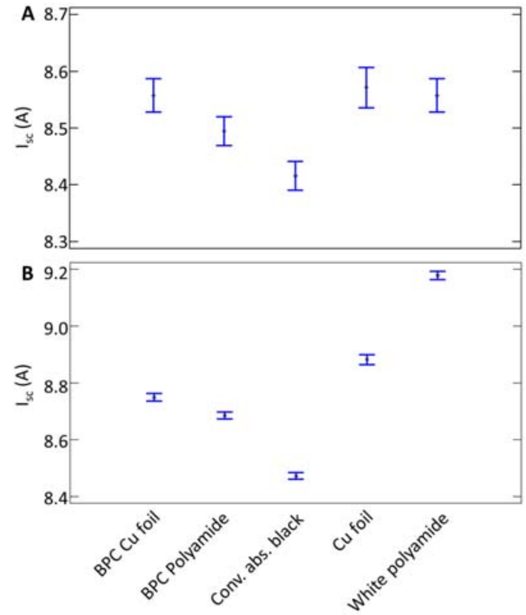

Figure 4: I_{sc} values recorded for the single cell laminates in case A) only the cell area and B) the full laminate is illuminated. In the latter case the illuminated area includes a 22 mm wide area around the cell where the backsheet is exposed to the incident light (see also Figure 2)

IR light will exit the rear of the cell and fall onto the backsheet which by reflecting the light back to the cell will aid the light management of the module. Case A corresponds to #5 in Figure 1, while case B combines #3, #4 and #5. The light that falls on the exposed backsheet area between the cells will include the VIS range as well. UV light will be filtered out by the glass and EVA layers above it. As indicated in Figure 1 only the light outside the escape cone will be trapped at the front glass-air interface.

For case A, the Cu foil, BPC Cu foil and White polyamide laminates display the highest I_{sc}. Although their IR reflection differs, the I_{sc} values found do not differ significantly among the groups and are around 8.57A. The BPC polyamide has a slightly lower I_{sc} value of 8.49A. The lower I_{sc} for the BPC polyamide as compared to the BPC Cu foil is in line with the lower IR reflection reported in Figure 3. All of the laminate configurations above clearly perform better than the conventional black laminate with an I_{sc} of 8.42A. In case B the differences in I_{sc} for the different types of laminates increase. As a consequence of the better reflection in the VIS range, the laminates incorporating the uncoated white polyamide and Cu foil outperform the all-black laminates. Although the reflection measured for the Cu foil is higher in a large part of the spectrum, the white polyamide back foil results in a higher I_{sc} when the full laminate area is illuminated. Presumably, what plays a role here is the broader range of high reflectance of the polyamide foil and a possible higher degree of Lambertianity. As was already the case when only the reflections from behind the cell were taken into account, the BPC foil based laminates clearly outperform the conventional black laminate. The BPC Cu foil yields a slightly higher I_{sc} than the BPC polyamide foil, 8.75 ± 0.01A vs 8.69 ± 0.02A, while for the conventional black

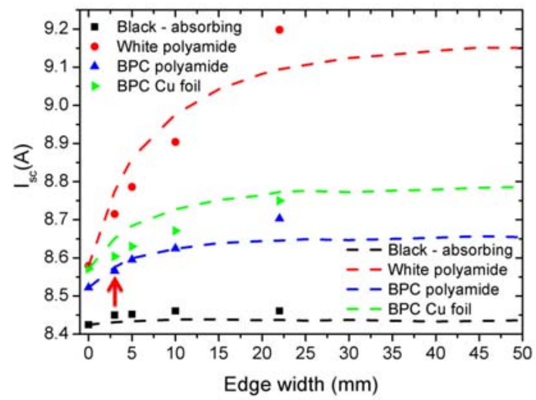

Figure 5: I_{sc} as function of the exposed edge width around the cell for different backsheets studied. The dashed lines are the result of a ray-tracing analysis using a simple model (for details see text).

laminates a (scaled) I_{sc} of 8.47 ± 0.01A is found. For each group of laminates one was selected for which a series of different sized masks was applied. In addition, ray-tracing simulations were performed to model the fraction of rays falling onto the cells after reflection from the backsheet for the different aperture areas. The measured and simulated data are included in Figure 5. In the simple ray-tracing model used here, the solar cell is modelled as a black absorber (in the 330 – 1100 nm spectral range, with an IQE 100%. This will result in an overestimation of the contribution of longer wavelength light to the I_{sc}. Therefore, it is expected that the model will overestimate the fractional increase in I_{sc} from the exposed backsheet area (in particular for the BPC foils). Furthermore, the model assumes Lambertian reflection by the backsheets and a flat interface between air-glass, any deviation from this will affect the fraction of light falling within the escape cone. Nevertheless, the simulations succeeded in reproducing the trends in the experimental data.
From Figure 5 one can observe that although the BPC Cu foil displayed significantly higher IR reflection than the BPC polyamide foil, the slope of I_{sc} vs. edge width is very similar. Compared to the I_{sc} at 0 mm edge width the I_{sc} at full laminate illumination is a factor 1.02 higher for both configurations. In addition, to the absolute reflection also the angular distribution of the reflected light is of importance for the foil's performance with respect to concentration. Therefore, we hypothesize that the BPC polyamide foil's reflection angular distribution is closer to Lambertian than for the BPC Cu foil.

Finally, we use the laminate data to make an estimate of the performance yield, which can be obtained from the application of the BPC foils. Since the typical-inter cell distances in a module are around 3 mm, we obtain from Figure 5 (indicated by the red arrow) an increase in I_{sc} of 1.4% and 1.8% for BPC polyamide and BPC Cu foil respectively with respect to the conventional black layout.

4 CONCLUSIONS

We have shown that the application of black, low IR absorption, powder-coatings to standard foils used in PV industry can be used to significantly reduce CtM losses for all-black modules. Upon the application of such foils the IR reflective properties of the underlying substrate are largely preserved. In comparison to the conventional, absorbing black foils an improvement in I_{sc} of 1.4 – 1.8% is expected on module level.

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