INVESTIGATIONS ON THE PHOTON-RECYCLING PROPERTIES OF DIFFERENT BACK-SHEETS

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ABSTRACT: In a state-of-the-art photovoltaic module the solar cell area accounts for about 85 to 90% of the total module area. The rest of the module area is dominated by the back-sheet. Light impinging onto the back-sheets is mostly reflected and a part of the reflected light is re-directed onto the solar cells. This photon recycling effect is well known, but the efficiency of this process is not well understood until now. In this paper we present the results of a study on the photon-recycling efficiency of different ISOVOLTAIC back-sheets and investigate the reasons for their varying optical performances. A series of mono-cell-modules with different back-sheets was manufactured and carefully investigated under Standard Test Conditions and by applying the Laser Beam Induced Current method. In addition, the scattering properties of the back-sheets were measured which are the basis for the modelling of the photon recycling efficiency. The experimental as well as the modelling results show good agreement. In particular it is shown the photon recycling efficiency within a module significantly depends on the type of back-sheet used. The average photon recycling efficiency of a typical module boarder region is found to range from about 19 to 23%, depending on the type of back-sheet used.

Keywords: Optical Losses, Module, c-Si, Ray Tracing

1 INTRODUCTION

Today the predominant photovoltaic (PV) module technology is based on crystalline Silicon (c-Si) solar cells in a flat-plate set-up. In flat-plate modules the solar cells are typically arranged in a matrix comprising of 6x10 solar cells. This solar cell matrix is embedded in an encapsulation material and is covered with a sheet of glass. The rear side typically is made of an electrically insolating back-sheet.

Not the total area of state-of-the-art modules is covered with c-Si solar cells. In particular, due to safety reasons, the frame regions of the modules must not be covered with elements which conduct electrical current. In Figure 1 a photo of the corner of a state-of-the-art flat-plate module is depicted, which clearly shows a part of the area not covered with solar cells.

Figure 1: A photo of the corner of a state-of-the-art flat-plate module is shown.

The border regions of a state-of-the-art c-Si module comprising of 60 solar cells typically contribute to about 9% of the total module area and corresponds to the most substantial cell to module loss [1]. However, light which is impinging onto the border region is not totally lost. In particular light is scattered at (white) back-sheets and to some extend the light is redirected onto the solar cells.

In literature several contributions on the photon recycling properties of back-sheets are found [1],[2],[3]. These approaches are typically based on experimental approaches and/or optical modelling, where the photon recycling of the back-sheet is simulated by ray-tracing. For the ray-tracing modelling known from literature the scattering properties of the back-sheets are considered to be lambertian. This assumption enables a straight forward ray-tracing simulation; however, it is an idealisation. This idealisation is acceptable when the back-sheet is a constant; e.g. when optimising the cell distance as found in [2],[3]. However, when the photon recycling properties of different back-sheets with varying scattering properties should be compared, the application of a lambertian scattering model might be insufficient.

In this paper we present the results of a study on the photon-recycling efficiency of different back-sheets by taking into account their individual scattering properties.

2 APPROACH AND METHODS

Experimental:

Four different types of white back-sheets from ISOVOLTAIC were investigated. These were integrated into single-cell modules comprising of 156x156 mm² c-Si solar cells. The IV curve of the (naked) cells was carefully characterised with a flash measurement system (Sinton FCT-350 Flash Tester).

Glass plates with a thickness of 3.2 mm and an area of 186x186 mm² were used. Thus the difference of the module area and the solar cell area accounts for about 42% of the solar cell area.

The IV curve of the single-cell modules was measured again at the same flash tester as already used for the characterisation of the solar cells. In Figure 2 a photo of a single-cell module is shown.

Figure 2: A photo of a single-cell module is shown.

In addition to IV flash tester measurements the single-cell modules were characterised by applying the Laser Beam Induced Current (LBIC) method. In particular the photocurrent of the modules was measured when illuminating the module at different positions with a collimated laser beam (wavelength 633 nm, perpendicular incidence and spot size about 0.5 mm). In Figure 3 a photo of the LBIC measurement set-up is shown.

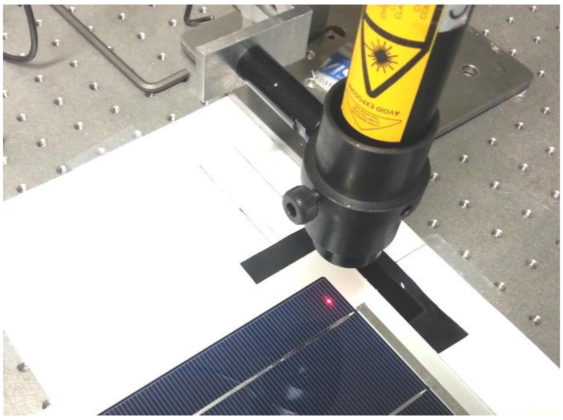

Figure 3: A photo of the LBIC measurement set-up is shown.

Moreover a LBIC characterisation was conducted at Fraunhofer ISE using a LOANA solar cell analysis system from pv-tools.

Simulation:

The estimation (simulation) of the optical photon recycling performance of different module back-sheets requires an accurate knowledge of the angular and total reflection properties of each back-sheet. The modelling could be basically done by a microscopic approach for subtle surface variations that yield a complex model of the back-sheet topography. Alternatively, accurate modelling can be accomplished by taking into account the actual measured bidirectional reflection distribution function (BRDF), which was done within the framework this work. The hemispherical scatter data of the different back sheets were obtained from measurements with an imaging sphere from Radiant Zemax, LLC. The samples were illuminated by a halogen lamp. The measurements were performed for illumination angles at 15, 30, 45, 60, and 75 degrees. From these measurements, the scatter behaviour of the back-sheets was modelled and implemented into the optical simulations taking into account the angular distribution of the reflected light and the total integrated hemispherical reflection (TIS) (see Figure 4).

In addition to the scattering properties as determined by the measurements, a complete single cell module was setup with physically reasonable properties for all other components in order to resemble the experimental conditions as good as possible: a 200µm thick Si cell with an area of 156 x 156 mm² Si cell was modelled including dispersion and internal transmittance via the complex index of refraction. The Si surface was textured with µ-pyramid structures (20µm base, 12µm height). The micro texture was coated with 75nm SiNx antireflection coating, also modelled from the complex index of refraction yielding realistic thin film spectral reflection behaviour.

The wafer backside was assumed to have a 50% reflection and a lambertian scattering characteristic. The electrodes (bus bar and fingers) were modelled according to real geometry and assumed to be diffuse white (95% TIS, lambertian angular characteristics). The Si cell was embedded in an EVA layer (1mm thick) with a constant index of refraction (n=1.483). On top of the EVA film a 3.2 mm thick N-BK7 glass is attached. The module has an overall size of 186 x 186 mm². The module was illuminated with a small (0.1mm diameter) collimated beam. The position of the light source was scanned across the module and the total absorbed flux inside the Si wafer was recorded as a function of the source position with a volume detector. Thus, the photon recycling power of the various back-sheets can be monitored and evaluated. All simulations were carried out with Zemax OpticStudio 14.2.

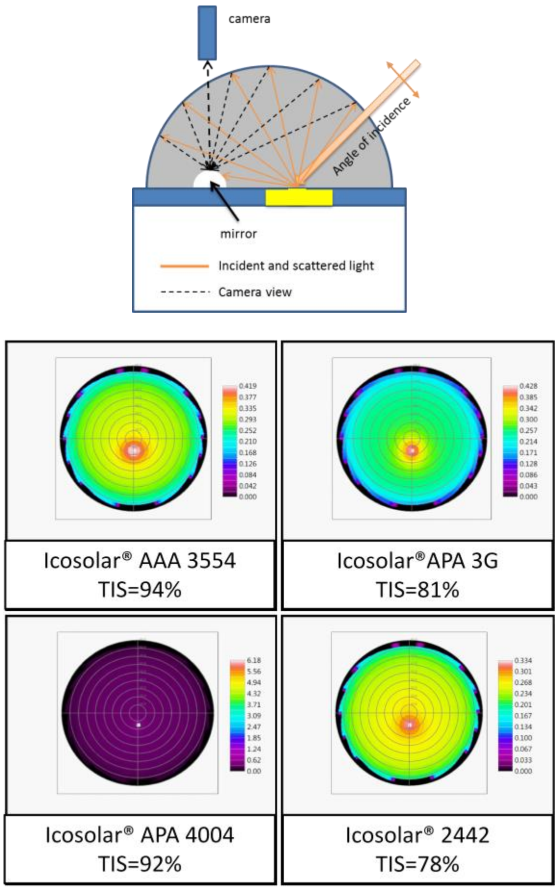

Figure 4: Top: Measurement principle of imaging sphere for BRDF determination. Bottom: retrieved scatter data

of the back-sheets shown at 15° angle of incidence. TIS denotes the respective total integrated scatter.

Obviously, the scattering properties of the individual back-sheets are different. The highest TIS was measured for the Samples of the back-sheet types Icosolar® AAA 3554 and APA 4004. However, the angular distribution of the light scattering is different for these two samples. The same is true for the other two samples which show a lower TIS. In particular the Icosolar® 2442 seems to scatter more light in wider angles than the APA 3G.

3 RESULTS

The short circuit current of the solar cells and the single-cell modules was measured with a cell flash tester. In particular every measurement was conducted four times and the arithmetic average was computed. The standard deviation of individual short circuit current measurements is found to be about 0.02 A. The resulting short circuit currents of solar cells and of the single-cell modules with different back-sheets are shown in Table 1.

Table 1: The average short circuit current (I_{SC}) of the modules with individual back-sheets and the corresponding naked cell short circuit current is tabulated

	I_{SC} Module	I_{SC} Cell
Icosolar® AAA 3554	9.372 A	8.506 A
Icosolar® APA 4004	9.422 A	8.528 A
Icosolar® APA 3G	9.342 A	8.504 A
Icosolar® 2442	9.332 A	8.527 A

Obviously, the encapsulation of the solar cells results in a plus of the short circuit current. Consequently, the positive effects of photon recycling and an improved optical matching of the anti-reflective coating outweigh reflection losses at the air-glass interface. Since the back-sheets are the only components which are different among the modules, the difference in the relative improvement in short circuit current can be directly related the individual back-sheets. The relative increase of the average short circuit current and the corresponding standard deviations are shown in Figure 5.

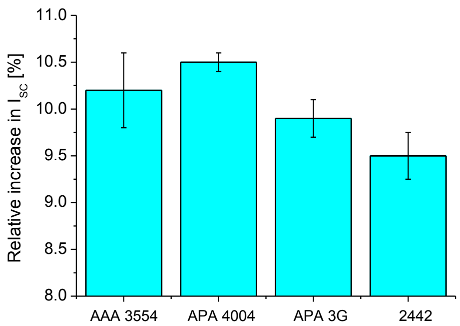

Figure 5: The relative increase in short circuit current is shown for the single-cell modules with different back-sheets. The arrow bars are derived from the standard deviation of repeated individual measurements.

The increase in short circuit current significantly depends on the back-sheet applied. The relative increase in current is ranging from 9.5% to 10.5%. Taking into account that the module area is 42% larger than the solar cell area one can derive an optical efficiency by dividing the relative current plus by the relative area plus. In particular this optical efficiency is found to range from 22.6 to 25.0% for the different back-sheets. However, since the current increase is the result of several effects (increased matching of anti-reflective coating, photon recycling of light reflected at grid fingers, reflection losses at glass, …) the absolute values cannot be directly related to the back-sheets.

An LBIC measurement allows to derive spatially resolved information and to investigate the absolute photon recycling efficiency of the back-sheets. The measured photocurrent of the single-cell modules is relatively constant when the laser beam is located at the active solar cell. However, also a significant photocurrent is measured when the laser is impinging the back-sheet which is a result of the photon recycling. In Figure 6 the LBIC measurement results (normalised to the photocurrent measured at the solar cell) are shown for the individual modules.

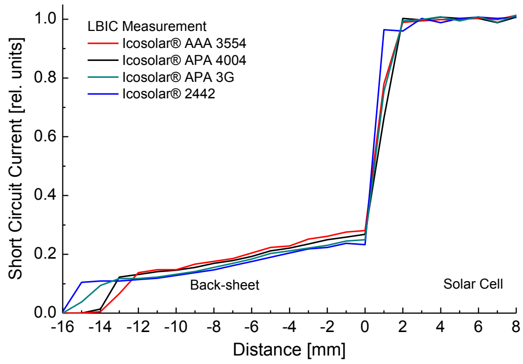

Figure 6: The short circuit currents are shown for different positions of a LBIC line scan. The values are normalised with respect to the current measured at solar cell positions.

Obviously, the photon recycling efficiency decreases with increasing distance to the solar cell. Please note, that due to slight variations in the position of the solar cell the drop to zero of the measured current (laser beam does not hit the module any more) is varying by ± 1 mm.

Since the short circuit current signal is normalised in Figure 6, the relative LBIC signal measured at back-sheet positions can be interpreted as photon recycling efficiency (PRE). With increasing distance from the edge of the cell this optical efficiency continuously decreases. For comparison the average of the normalised photocurrent is calculated for a boarder width of 12 mm. In order to reduce the impact of statistic measurement errors the PRE was derived from averaging over about 100 LBIC line scans at different positions (automatized LBIC measurements). This PRE efficiency is tabulated in Table 2.

Table 2: The average photon recycling efficiency and the corresponding standard deviation derived from LBIC measurements is tabulated for the individual back-sheets

	avg. PRE	SD
Icosolar® AAA 3554	22.0%	1.3%
Icosolar® APA 4004	22.9%	1.3%
Icosolar® APA 3G	20.9%	1.2%
Icosolar® 2442	20.8%	1.1%

The scattering properties of the back-sheets were measured by applying the method described above. The back-sheets are varying substantially in terms of reflectivity and scattering properties as seen also in Figure 4

In optical ray-tracing simulations the amount of light absorbed in the solar cell is calculated for different positions of incidence. In particular the PRE was calculated for the same wavelength and measurement positions as conduced in the LBIC measurements. In Figure 7 the modelled PRE is shown for the individual back-sheets.

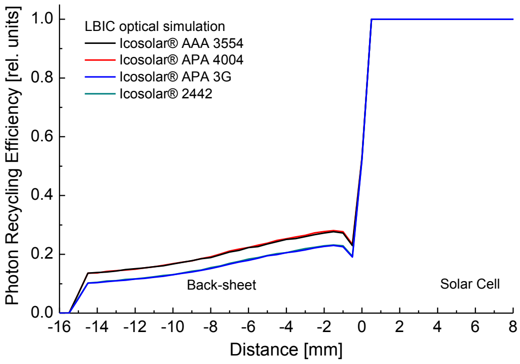

Figure 7: The photon recycling efficiency derived from optical modelling is plotted.

When comparing the modelling results (Figure 7) to the results of the normalised LBIC measurements (Figure 6), one can see that these are in very good agreement. When calculating the average PRE for a border region of 12 mm the results tabulated in Table 3 are derived:

Table 3: The average photon recycling efficiency derived from optical ray-tracing simulations are tabulated

	average PRE
Icosolar® AAA 3554	22.9%
Icosolar® APA 4004	22.7%
Icosolar® APA 3G	19.0%
Icosolar® 2442	18.8%

5 CONCLUSIONS

The experimental as well as the modelling results show good agreement. In particular it is shown the photon recycling efficiency within a module significantly depends on the type of back-sheet used. The average photon recycling efficiency of a typical module boarder region found to range from about 19 to 23% depending on the type of back-sheet used. Referred to the typical 9% of area share for the border region of a state-of-the-art module, this accounts for a range of 1.7 to 2.1% in current plus which potentially is achievable when using different types of the investigated back-sheets.

6 ACKNOLEDGEMENTS

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