PLANAR PHOTONIC STRUCTURES LIGHT MANAGEMENT IN PHOTOVOLTAIC MODULES

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ABSTRACT: A substantial part of the light impinging the surface of a state-of-the-art photovoltaic module is not absorbed by the solar cells. Basically, output power is lost when part of the incident light does not reach the solar cells. Here we present an approach to increase the light harvesting of photovoltaic modules. Planar light redirecting structures fabricated by UV imprint lithography aim to decrease the optical losses especially in the region of the module border (next to the frame). The approach is based on the integration of optical structures inside the module, that shall redirect light, which otherwise would impinge the electrically inactive border region. The planar optical elements reflect light at such angles that internal reflection at the front surface of the cover glass occurs. From there the light is reflected back to the solar cell and contributes to the generated photocurrent. Based on LBIC measurements it is found that a reflective saw-tooth structure can utilize about 5 times more light hitting a 1 cm wide border region next to the cells than a white back-sheet. Moreover an alternative (patent pending) approach is presented which does not require a reflective coating.

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 at the front side. The rear side typically is made of an electrically insolating back-sheet or another glass plane.

Not the total area of state-of-the-art module is covered with c-Si solar cells. In particular due to safety reasons the border 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 shown which clearly shows a part of the area not covered with solar cells.

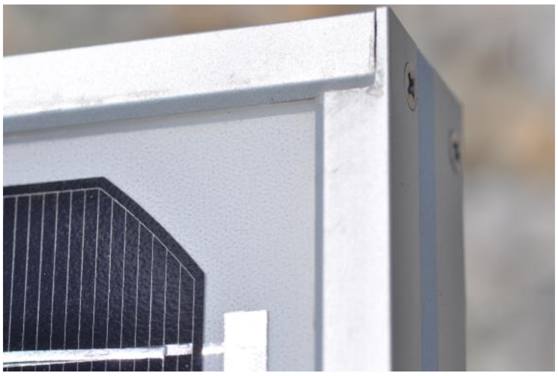

Figure 1: A photo of the corner of a state-of-the-art flat-plate module is shown.

The width of this border region is usually ranging from 16 mm to 40 mm, which contributes to about 5 to 12% of a total module area of 1.6 m². Sunlight impinging this electrically inactive border region of the module is mostly reflected or absorbed and does almost not contribute to the photocurrent of the module. Vice versa the photocurrent of a state-of-the-art flat-plate module can be increased by about 10% if all the light impinging the border regions of the module can be redirected onto the solar cells.

In literature many approaches to utilize light which does not directly impinge on the active solar cell area are described. In particular a bunch of patents disclose reflective films which redirect light from areas in-between solar cells via total internal reflection at the glass-air interface [1],[2],[3]. Usually the desired redirection of light is realized by reflective prisms with angles of about 120°. This light management approach is also well known for light harvesting strings [4]. The drawback of using 120° reflective prisms is that in the border regions of the photovoltaic modules about 50% of the light is directed in the wrong direction (away from the cells).

In this work we present results on planar light management structures for an increased light harvesting from the border regions of photovoltaic modules.

2 APPROACH AND EXPERIMENTAL

The approach on redirecting light from the edges of a photovoltaic module onto the solar cells relies on reflective saw-tooth structures. In particular sunlight which impinges a structured film with a reflective coating is reflected onto the glass-air interface where it is totally internally reflected (see sketch in Figure 2). The asymmetric structure allows the utilization of a major part of the light impinging the border regions of a photovoltaic module.

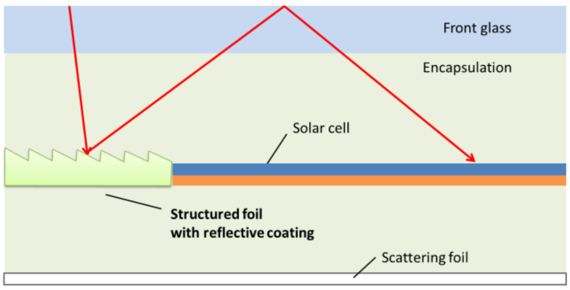

Figure 2: A sketch of the approach applied to utilize light impinging the border region of a photovoltaic module is shown.

The planar light redirecting films are made by UV

Imprint-Lithography resulting in films with high surface quality. In a first step of the imprint process, we use Polydimethylsiloxan (PDMS), which is transparent for UV radiation, in order to fabricate a flexible PDMS mould from a PMMA master. In the further procedure we use this PDMS mould as working stamp to produce ORMOSTAMP structures on a PET substrate. ORMOSTAMP is a hybrid polymer from Micro Resist technology specially developed for imprint applications. This material is hardened by UV exposure. The saw-tooth films are coated with a highly reflective 600 nm silver layer by applying physical vapour deposition. A cross section of the manufactured film is shown in Figure 3.

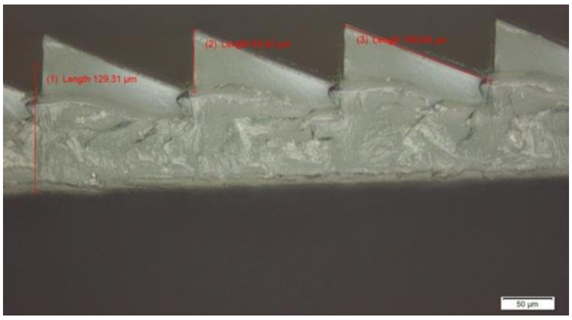

Figure 3: A cross section of the manufactured film is shown. The angle of the saw-tooth is 24° and the pitch is 150 µm.

For testing the performance of the manufactured films lab-scale modules were manufactured. This lab-scale module comprise of a small solar cell (20x20 mm²) laminated behind a 4 mm glass plane with an area of 60x60 mm². The rear-side of the module is made of a white back-sheet. In particular one reference module was manufactured and one module with incorporated light guiding films (such as shown in Figure 3). Photos of these two modules are shown in Figure 4.

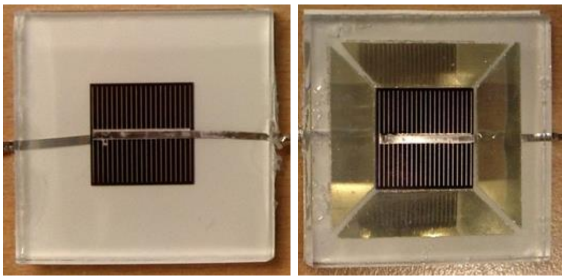

Figure 4: Photos of lab-scale modules used for evaluating the light guiding film are shown. Left: Reference module. On the right side one can see a module with light guiding films incorporated.

The lab-scale modules are characterised by applying the Laser Beam Induced Current (LBIC) method. In particular the modules were measured by Fraunhofer ISE using a LOANA solar cell analysis system from pv-tools.

3 RESULTS

LBIC measurements of the above described labscale modules were conducted. In particular the photocurrent of the cells was measured, when scanning the module with laser-beams of 6 different wavelengths (405 nm, 532 nm, 658 nm, 780 nm, 940 nm and 1064 nm) at almost perpendicular incidence angle. An area of about 50x50 mm² was scanned (resolution: 260x260 points).

In Figure 5 a line scan of the LBIC measurements is shown for the reference sample. The line scan is in the conducted through the middle of the cell - perpendicular to the orientation of the bus bar. In Figure 6 the same is shown for the lab-scale module with reflective saw-tooth films incorporated.

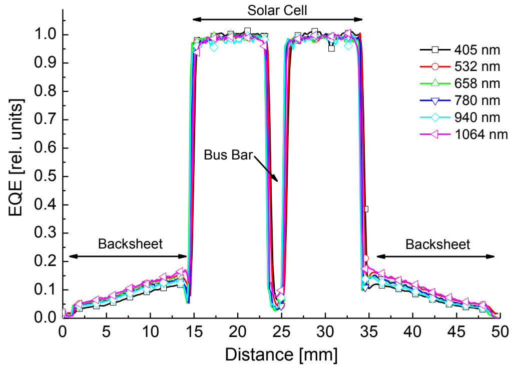

Figure 5: A LBIC line scan is shown for the reference labscale module.

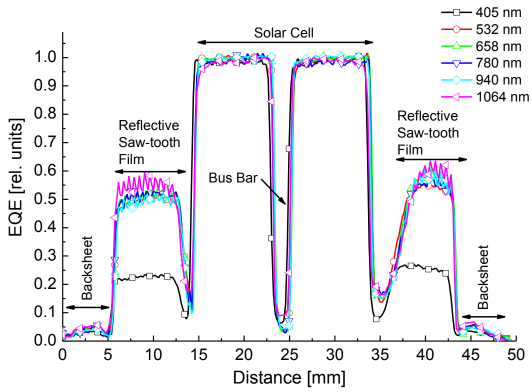

Figure 6: A LBIC line scan is shown for the labscale module with reflective saw-tooth films integrated.

Obviously the measured photocurrent (which directly correlates to the external quantum efficiency (EQE)) is quite constant when active solar cell areas are scanned. When bus bar and back-sheet areas are measured the EQE substantially decreases. However, due to scattered light which impinges the solar cell, also a significant photocurrent signal is measured when these electrically inactive areas are scanned. A comparison of the reference sample and the sample with the reflective saw-tooth film clearly shows that the light guiding film redirects about 5 times more light onto the cell than the back-sheet.

Since the EQE (photocurrent) measurements shown in Figure 5 and Figure 6 are normalised to the LBIC signal measured at the active solar cell area, the relative EQE measured at electrically inactive positions corresponds to the optical efficiency in “photon recycling”. In Figure 7 the average optical efficiency of a white back-sheet and the reflective saw-tooth film is shown. In both cases the arithmetic average of the relative EQE (see Figure 5 and Figure 6) for a 1 cm border region next to the cell were calculated.

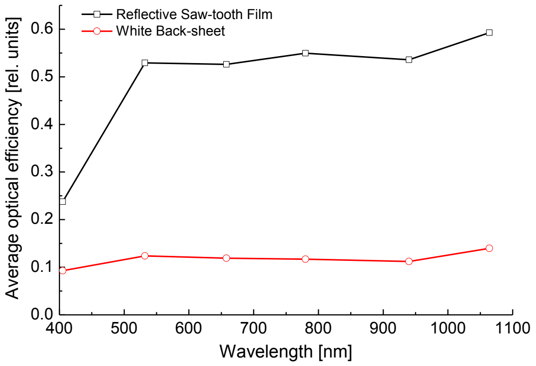

Figure 7: The average optical efficiency of a 1 cm border region next to the solar cell is shown for a white back-sheet and for a reflective saw-tooth film.

For wavelengths > 500 nm the derived optical efficiency is relatively constant and about 50% for the reflective saw-tooth film and 10% for the white back-sheet. In contrast the optical efficiency is lower for shorter wavelengths and in particular for the saw-tooth film it substantially decreases to about 25%. The reason for this wavelength dependence might be related to absorption losses in the metallisation of the saw-tooth film.

4 DISCUSSION

As shown above a part of the light which impinges on electrically inactive areas of PV modules can contribute to photocurrent of the solar cells. When multiplying the derived optical efficiency and the relative share of the electrically inactive border region of a state-of-the-art module (see introduction) the photocurrent-contribution from the border region can be estimated. For a white back-sheet the border region of a module can increase the photocurrent by about 0.5 to 1.2% which is good agreement to recently published experimental results on this topic [5].

If the border region of a state-of-the-art PV module would be completely covered with the above described reflective saw-tooth films the border region could increase the photocurrent by 2 to 6%. Consequently in the best case the photocurrent and probably also the power of a state-of-the-art flat plate module can be increased by up to 5% when incorporating the reflective saw-tooth films at the border regions of the module. This increase could be even higher if the optical efficiency of the light guiding films could be improved.

Limitations in optical efficiency by the above described reflective saw-tooth films are resulting from imperfections in the reflectivity and surface roughness. Moreover the structure itself is limiting the maximal optical efficiency due to self-shadowing effects as sketched in Figure 8. This self-shadowing effect causes that even for a perfect structure; the optical efficiency of a saw-tooth structure will be lower than 70%.

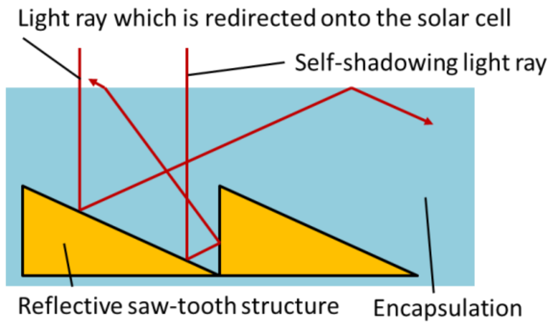

Figure 8: A sketch illustrating the self-shadowing of the saw-tooth structure.

The coating of reflective films (metallisation or dielectric multi-layer stacks) usually require vacuum processes which are not optimal from an economical point of view. Moreover a metallisation might be a safety risk, since it is electrically conductive. Therefore a light guiding film is desired, which can achieve higher optical efficiency and which does not require vacuum processes for manufacturing.

5 ALTERNATIVE APPROACH

An alternative optical approach has been developed which can be at least as efficient as the above described saw-tooth structures and which does not require vacuum processes. This approach relies on a combination of total internal reflection and refraction. In particular the light guiding elements are prism structures filled with air or gas within the encapsulation. A sketch of this approach is shown in Figure 9.

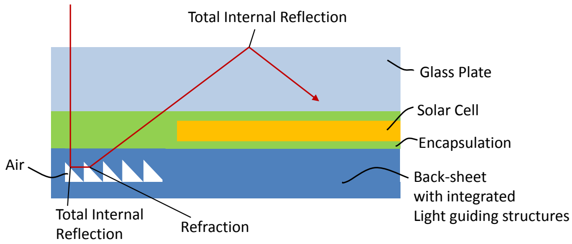

Figure 9: Light guiding elements comprising of air prisms integrated in the back-sheet of a module are shown (**Patent Pending**).

One possible way to integrate the air-prisms into the module set-up is to fabricate a film which is partly structured with saw-tooth having an angle of about 45°. This structured transparent film is laminated to a back-sheet and due to the structure some air is trapped in between the two films. Light which impinges the tilted surfaces of the structure is totally reflected and impinges the tilted surface of a neighbour prism, where it is refracted towards the glass-air interface.

Optical ray-tracing simulations on this approach show that the optical efficiency of the above described air-prism approach can be more than 80%. In Figure 10 the optical efficiency of a 45° air-prism film is shown for a varying board width.

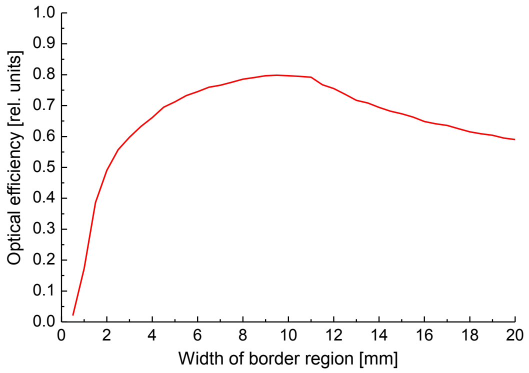

Figure 10: Optical simulation results of the optical efficiency of the air-prism approach sketched in Figure 9.

In particular the optical efficiency is quite low for narrow boarder widths, since perpendicular light rays are re-directed in angles of > 70°, which is positive for the wave-guiding at the glass-air interface. However, due to these high re-direction angles shadowing effects at the back-side of the solar cells substantially limit the optical efficiency for border regions with narrow width. With increasing border width the optical efficiency increases and reaches a maximum of more than 80% for a border width of about 10 mm. For border widths > 10 mm the optical efficiency decreases due to an increasing amount of re-directed light rays impinging the air-prism structure a second time.

6 CONCLUSIONS

The presented approach of integrating reflective saw-tooth films in a PV module is shown to be an effective way to recycle photons from the border region of a module. In particular the films manufactured are about 5 times more efficient than white back-sheets. Moreover an alternative approach relying of air-prisms integrated in back-sheets is presented. This alternative (patent pending) approach allows achieving higher optical efficiencies and does not require a reflective coating. Consequently it might also be of advantage in terms of manufacturing costs.

7 ACKNOLEDGEMENTS

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