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Optimizing Scattering Behaviour of Encapsulant for Maximum PV Energy Yield

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Abstract Nowadays, material manufacturers are engineering module materials to optimize the energy production of the PV modules. One of the elements which can be influenced is the optical scattering of a material. In this study, we quantified the effect of a scattering front encapsulant on the energy production of PV modules. First, a wavelength-dependent scattering model was developed in the ray-tracing software PVlighthouse. This model was used to find the optimal scattering conditions, looking at the photo-generated current for a glass-glass PV module with flat front surface. It was shown that a gain of $+0.63$ mA/cm^2 can be obtained for optimal scattering conditions. The scattering is mostly beneficial when the light strikes the module surface at a perpendicular angle. The outcome of the optimization study was implemented in IMEC's energy yield simulation framework. This framework was used to estimate the energy gain of PV module with scattering front encapsulant when installed in Kuwait's desert. It was shown that an energy production gain of 1.8% can be expected in case of a glass-glass module with flat front surface and ARC coating.

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1 Introduction

To tackle the worldwide challenge to provide a sustainable and economically viable energy supply, photovoltaic (PV) modules are being deployed faster than ever before, showing an astonishing annual growth reaching 95 GWp in 2017 [1]. Currently, silicon-based PV modules dominate the market, and it is expected that this will continue in the coming decade [1]. As the levelized cost of electricity of PV systems is strongly depending on the cost/Wp of the PV modules, numerous research institutes and PV module productions companies focus on improving the efficiency of silicon-based PV modules, hereby reducing the cost-price of PV devices.

For a high PV energy production, one can improve the conversion efficiency of the solar cells. Another way of maximizing the yield is to optimize the module itself and, more specifically, module materials. Researches focusses on improving, e.g., the reflectivity of the backsheet, reducing the glass and encapsulant absorbance. Yield improvement could also be obtained by introducing optical scattering in the front encapsulant layer; however, not much is known about actual improvement of this feature. In this chapter, we will study the effect of optical scattering in the front encapsulant layer on the energy production of PV modules. First, we will develop a ray-tracing model which incorporates the wavelength-dependent scattering, followed by an optimization study. The ray-tracing model will then be used to simulate the energy yield for various scattering scenarios using IMEC's energy yield simulation framework. The outcome of this study can be used by module and module material manufacturers to optimize PV modules.

2 Energy Yield Framework

2.1 General Description Framework

IMEC's PV energy yield simulation framework will form the bases to translate the scattering effect into outdoor energy yield gain. The Electrical, Optical and Thermal (EOT) modelling approach used in this chapter uses meteorological data (ambient temperature, irradiance and wind speed and direction) as input for the environmental conditions. Material properties (optical, thermal and electrical constants, thickness, etc.) and cell and module technology parameters (cell performance, temperature coefficients, EQE, etc.) serve as input to represent the PV module technology under evaluation. A full description and demonstration of this modelling approach can be found in [2, 3].

In the approach, every solar cell in the PV module is modelled individually to be able to simulate the effect of partial shading on the energy production [4]. The individual sub-models are both thermally and electrically coupled to create the model of a full module. The optical part of the model calculates the light absorption, heat and carrier generation in each layer of the PV module. The result is used by the thermal and the electrical parts of the model. The thermal part of the EOT model consists of an RC-equivalent thermal network that incorporates the heat capacity of each element and the conduction, convection and radiation of heat both within the module and from the module to the environment. Next to that, the thermal circuit also takes into account reduction of heat generation due to the dissipation of electrical energy in the electrical load and the thermal state of the PV module. Thermal resistances and capacities in the thermal circuit are equal to the physical value of each layer in the module. By incorporating the thermal capacity of each layer, thermal state effects are integrated. The thermal network is able to calculate the solar cell temperature as a function of illumination, ambient temperature, sky temperature, wind speed and direction, electrical operation point and thermal state. The well-known (1- or 2-) diode model is used to describe the electrical part of the PV module. Parameters of the diode model are being varied depending on solar cell temperature and illumination.

3 Intra-layer Optical Scattering

3.1 Wavelength-Dependent Scattering

Optical properties of materials can be influenced by varying manufacturing parameters, composition or physical dimensions. Not only the wavelength-dependent transmittance and reflectance can be engineered, but also the internal optical scattering can be influenced by varying production parameters. Even more, the optical scattering can be varied as a function of the wavelength. An example of an encapsulant with wavelength-dependent optical scattering is displayed in Fig. 1.

3.2 Optical Scattering Model

This scattering behaviour can be beneficial as it enhances the optical path and thus has the potential to reduce optical losses in the PV module. As the scattering properties of the front encapsulant can be engineered to enhance or to limit scattering, we would like to optimize this effect to obtain the highest outdoor energy yield production. As outdoor tests are time-consuming and sometimes difficult to estimate trends, we have extended the existing energy yield modelling framework to be able to estimate the effect of scattering encapsulants on the PV energy yield.

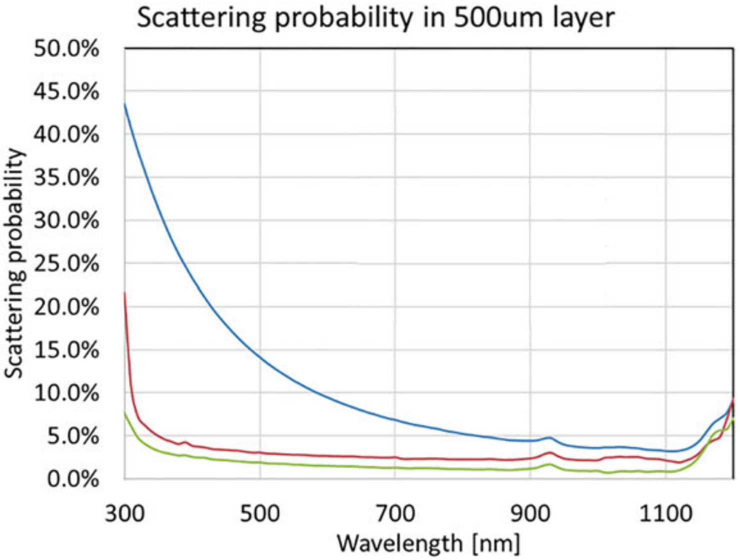

Fig. 1 Wavelength-dependent optical scattering of PV module encapsulants, measured using absorbance, reflectance and transmittance measurements. With [red] standard EVA encapsulant, [green] standard polyolefin encapsulant and [blue] scattering encapsulant

3.3 Scattering Implementation in PVlighthouse

As mentioned in Sect. 2, the energy yield model uses the layer properties in combination with the optical properties to estimate the reflectance and absorbance in each layer. For this estimation, the commercially available PVlighthouse software is being used [5]. This powerful simulation package is capable of estimating the required parameters but does not allow users to implement wavelength-dependent scattering properties; only scattering using a fixed ratio is allowed. Therefore, we implemented an artificial layer with half the thickness of the front encapsulant and provided this layer with texturing at the interface of both front layers. Figure 2 shows a snapshot of the structure used for the ray-tracing simulations. Note that we analyzed the scattering effect on a standard glass-glass module with 3.2 mm thick front and back glass (no antireflection coating), 450 µm front and back encapsulant, and 180 µm thick monofacial PERC solar cell. Furthermore, the simulation environment assumed ‘perfect mirror’ boundary conditions at the sides of the modules, and so the results are representative for cells inside the PV module.

As we have a textured interface between the front encapsulant layer, varying the refractive index of the ‘second’ front layer will promote or limit scattering. The wavelength-dependent index was gradually varied using the following correlation:

$$n_{sc}(\lambda) = n_{EVA}(\lambda)\left[1 + MF\left(\lambda_f - \lambda\right)\right]$$

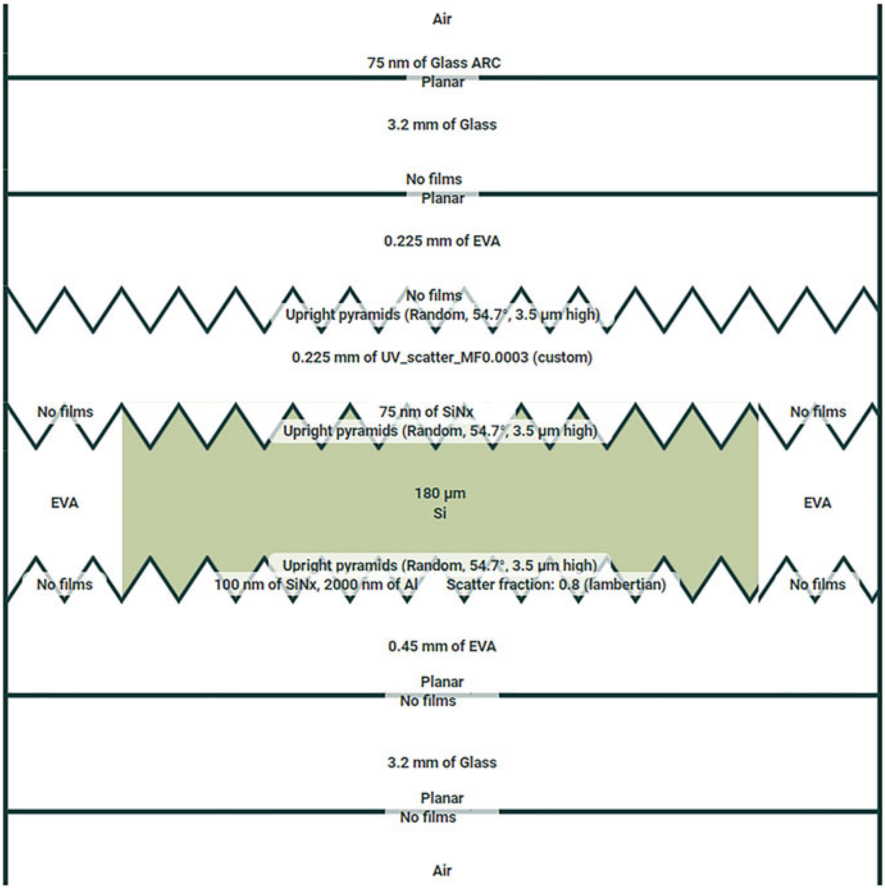

Fig. 2 PV module structure used to perform ray-tracing simulations in PVlighthouse

with $n_{sc}(\lambda)$ the refractive index of the bottom layer, $n_{EVA}(\lambda)$ the refractive index of EVA, *MF* a multiplication factor, λ_f the highest wavelength of the interval and λ the optical wavelength. *MF* is varied to have various scattering modes. The input parameters ($n_{sc}(\lambda)$) used for the optical simulations are displayed in Fig. 3.

3.4 Effect of Scattering on Photo-Generated Current Density

The manipulated optical constants of the bottom layer were implemented in the ray-tracing environment. The photo-generated current density was calculated for an AM1.5 solar spectrum, perpendicular to the surface. Next to that, the ray-tracing

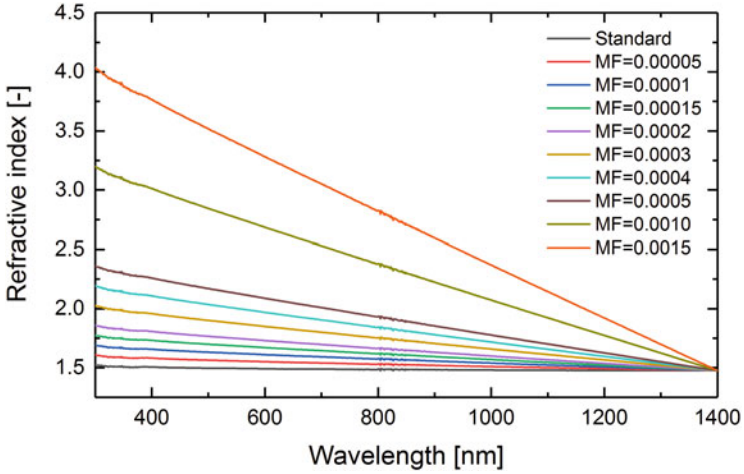

Fig. 3 Refractive index for various *MF* values. The displayed parameters were used as optical properties of the bottom front encapsulant layer

simulations were also used to extract the optical front (reflective and escape) losses of the PV module. The simulation results for various *MF* constants are displayed in Fig. 4.

Figure 4 shows the effect of the scattering on the photo-generated current. Up to a *MF* value of 0.0004, the scattering has a positive effect on the current generation. The enhanced optical path in the modules prevents that light is reflected at the rear glass layer and at the cell, resulting into a reduction of the escape losses, followed by an increase of the photo-generated current.

For *MF* factors higher that 0.0004, the photo-generated current starts to decrease, showing an optimum in the generation profile. The decrease is caused by additional internal reflection at the artificial interface of the front encapsulant layer. The difference in refractive index between the two layers is substantial (0.7 difference at 250 nm; see Fig. 3); hence, more light is reflected at the interface leading to more front escape losses

3.5 Angular Dependency Scattering

As mentioned in the section above, the scattering in the front enhances the optical path length in the PV modules resulting in less front escape losses. The PVlighthouse simulations show that there is an optimum for the scattering effect. The results were obtained by applying an AM1.5 spectrum perpendicular to the surface. It is expected that the scattering effects depend on the incident angle of the incoming light. This was investigated by varying the incident angle between 0° (perpendicular

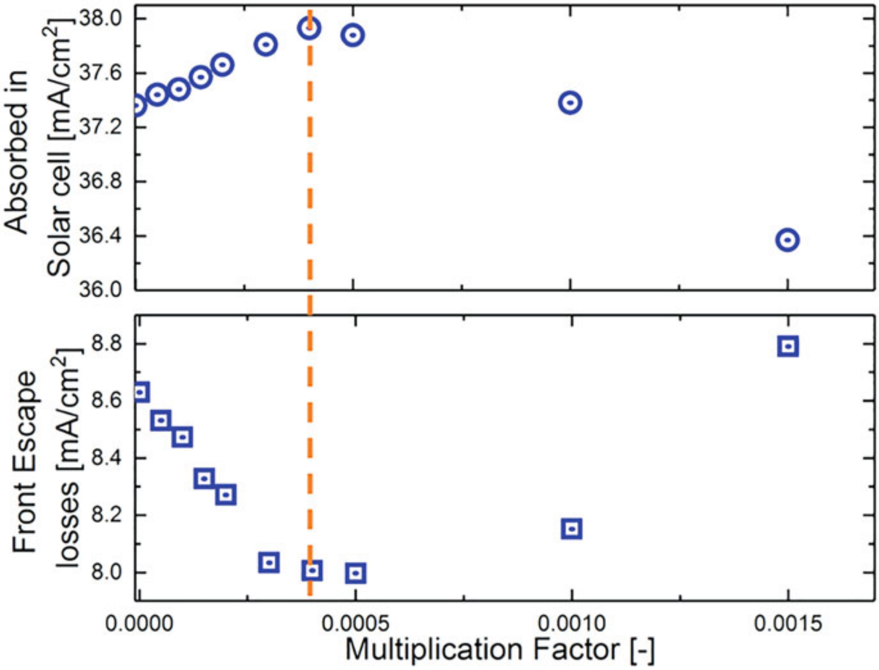

Fig. 4 Results of ray-tracing simulations for different values of *MF*: [top] photo-generated current and [bottom] front escape losses

to the surface) and 90°. The optimal scattering conditions ($MF=0.0004$) were implemented to demonstrate the most extreme case. Figure 5 shows the front escape losses for the standard EVA and the optimal scattering encapsulant. Note that the figure shows the absolute values; due to the angle variation, the light intensity on the modules surface decreases hereby also the absolute escape losses. To gain more insight, the relative difference between the two cases was calculated and also displayed in the bottom graph of Fig. 5.

The figure shows an overall decrease of the front escape losses as a function of the incident angle. As mentioned above, this trend is caused by a reduction of energy that reaches the module surface, and therefore, the absolute total amount of energy escaped from the front is reduced.

More important is the difference between the two simulation cases; this difference reduces for higher-incident angles. As discussed in the previous section, the optical scattering of the front encapsulant layer enhances the optical path in the modules and hereby improved photo-current generation. When the light hits the surface under a certain angle, inherently, the optical path is enhanced, and thus, scattering is less beneficial for situation where light has a higher angle.

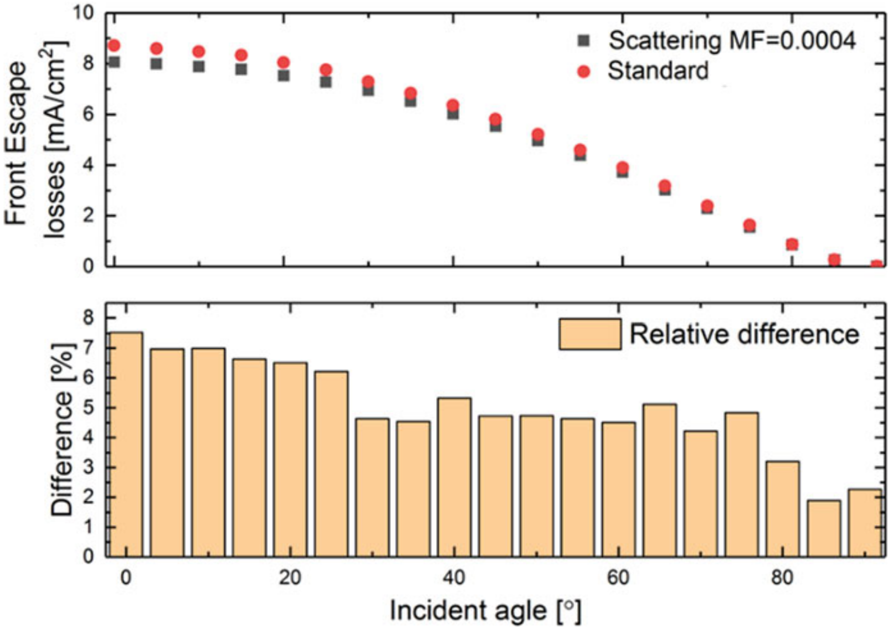

Fig. 5 Front escape losses for a PV module with a standard EVA front layer and one module with optimal scattering. The bottom part shows the relative differences between both cases

4 Energy Yield Simulation Results

In the previous section, an optical scattering model in PVlighthouse was developed and used to estimate the benefits of front encapsulant with optical scattering. The simulation results showed there exists an optimal scattering condition in which the maximum photo-generated current can be obtained. In this investigation, we focussed only on the optimal current; however, this gain cannot be directly translated into energy yield gain as, e.g., a higher current also results in a higher operating temperature, followed by a reduction of conversion efficiency.

Therefore, IMEC's energy yield estimation framework was used to quantify the scattering gain. Three different scenarios were investigated: 60-cell glass-glass modules with or without ARC coating and one case with textured front glass. Layer thicknesses are equal to the situation shown in Fig. 2. For the three different scenarios, the effect of the scattering front encapsulant was tested. The optimal scattering conditions (*MF*=0.0004) were implemented at the different scenarios.

The climate data, the year 2014 from 1 January until 31 December, recorded by Kuwait Institute for Scientific Research (KISR) at their Shagaya renewable energy park location, was used to test the potential of those modules in the MENA region. The simulated modules face south, and they are tilted at 30° from horizontal, which is optimal for the highest annual in-plane insolation under the latitude of Kuwait

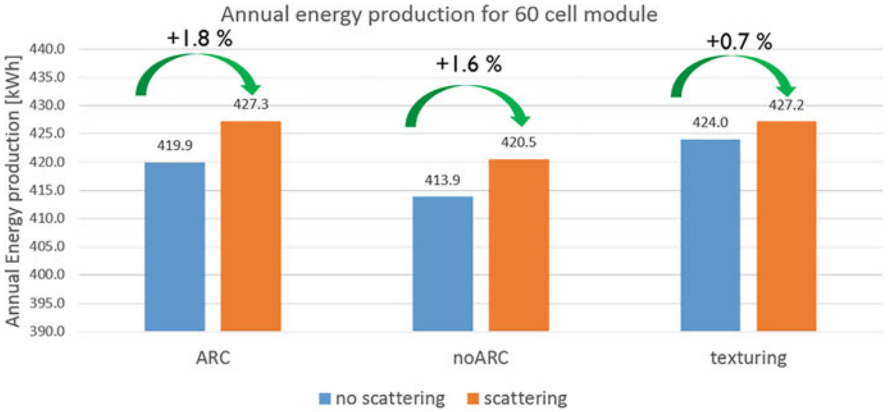

Fig. 6 Energy yield simulation results for the three different scenarios: glass-glass PV modules with a flat front and with or without an ARC coating and the same module with a textured front

City 29,33°. The ground surface albedo is assumed to be 0.2. The diffuse component of the in-plane irradiance is computed by means of the Perez model [6, 7]. The simulated energy production of a 60 cell PV modules for the different scenarios is shown by Fig. 6.

Figure 6 shows that for all the scenarios, the scattering front encapsulant is improving the energy production. The highest improvement was demonstrated for the case with flat glass front and ARC coating. As in this case, the most light enters the module structure, and therefore, the scattering of the front encapsulant has in this situation the most effect on the energy production. As expected, the lowest improvement was found with the textured front case. Nevertheless, there was still a 0.7 %abs improvement demonstrated for this case.

Note that comparable results were obtained for the ARC and the texturing cases. This indicates that a textured front glass can be replaced by an ARC-coated flat front glass in combination with a scattering front encapsulant. This might be beneficial for the production costs as no texturing step would be required in this process.

5 Discussion

The presented results were solely based on simulation (apart from the measured scattering example behaviour of the novel encapsulant layer). Thus, the results and the optimal conditions are not linked to any real-life material or process window. The follow-up of this research will focus on validating the results and on translating the optimal scattering conditions into material properties.

The study showed that scattering is mostly beneficial when the light strikes perpendicular on the PV module surface. This makes the technology extremely suitable for PV systems with one- or two-axis tracing devices. As those modules are always pointed towards the sun, encapsulant scattering will strongly enhance the energy production. Currently, the modelling framework is being extended to be able to quantify the scattering effect in PV systems with tracking devices.

6 Conclusions

In this study, we quantified the effect of a scattering front encapsulant on the energy production of PV modules. First, a wavelength-dependent scattering model was developed in the ray-tracing software PVlighthouse. This model was used to find the optimal scattering conditions, looking at the photo-generated current for a glass-glass PV module with flat front surface. It was shown that a gain of $+0.63$ mA/cm^2 can be obtained for optimal scattering conditions. The scattering is mostly beneficial when the light strikes the module surface at a perpendicular angle.

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