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Investigation of the short-circuit current increase for PV modules using halved silicon wafer solar cells

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ABSTRACT

It is well established that using halved silicon wafer solar cells in a photovoltaic (PV) module is an efficient way to reduce cell-to-module resistive losses. In this work we have shown that PV modules using halved cells additionally show an improvement in their optical performance, resulting in a higher current generation. We attribute this increase in current to gains in light reflected from the backsheet area. An optical model is presented that quantitatively determines the influence of the backsheet on the short-circuit current of a PV module. We find that, for an accurate prediction, several factors have to be taken into account, including the geometry of the module, the backscattering properties of the backsheet and the illumination spectrum. Particularly the angularly and spectrally resolved scattering properties of the backsheet are shown to have a large impact on the current generation. Furthermore, light beam induced current (LBIC) measurements are used to test the backscattering properties of the backsheet and also the influence of the illumination spectrum. LBIC measurements are also used to verify the simulation results, giving good agreement. Thus the design of a PV module can be optimized by simulation. A standard full-size cell module and a halved-cell module with optimized cell spacing are fabricated. Compared to the standard module, the half-cell module is shown to have 4.60% more power (315.3 vs. 329.8 W), 1.46% higher fill factor (75.5 vs. 76.6%), and 3.08% more current (9.08 vs. 9.36 A).

1. Introduction

In order to ensure the long-term competitiveness of the photovoltaic (PV) industry, the cost of PV electricity must be further reduced. Such reduction can emerge from two aspects: (i) improved solar cell and module power output; (ii) reduction of manufacturing costs [1]. One method to improve PV module power is to produce PV modules using halved silicon wafer solar cells. It is already known that by using halved cells instead of standard full-size cells, the cell-to-module power loss can be noticeably reduced, by reducing electrical series resistance related losses [2,3]. In the present work we have shown that, in addition to an improved fill factor due to the reduced power loss on the bussing ribbon, PV modules using halved cells also generate a higher current.

In this work, optical simulation is used to study the optical characteristics of a PV module. Optical studies for PV modules have also been done before to solve PV module related problems. In Ref. [4] a simulation tool was presented to test various types of encapsulation materials and front covers. In Ref. [5], the optical losses of encapsulated solar cells were calculated by an optical model. In this work, we focus on the amount of light that is scattered by the backsheet area and reflected to the solar cell area again. It is known that light scattered from the exposed backsheet of a PV module (see Fig. 1(a)) can significantly enhance the module's short-circuit current. However, there is still a need to precisely determine this amount of light so that the power output of a PV module can be optimized. The influence of the exposed backsheet area on the short-circuit current of a PV module has been investigated before [6–10]. Experimental results, however, were only provided in Refs. [6,7]. Ray tracing simulation was used in Refs. [8,9], however, the light spectrum and the angular dependent scattering properties were not considered in both papers, and only mini-modules were investigated in Ref. [8]. Refs. [10,11] include the wavelength dependent reflectance of the backsheet in the model, and it also indicates that just considering the spectral dependence is not sufficient for a complete description.

The present work is based on the methods introduced in Refs. [8–10], and introduces an extended model. We show that mainly

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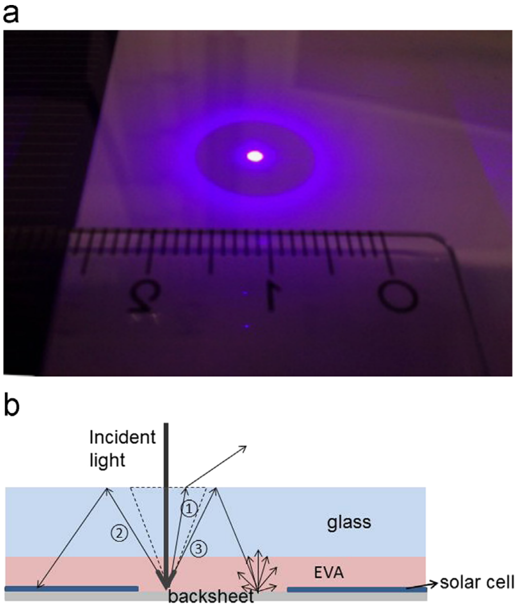

Fig. 1. (a) A photograph demonstrating the scattering of light by the backsheet of a silicon wafer PV module. (b) Light paths within a PV module. Light incident on the backsheet area between the solar cells is randomly scattered. The scattered light within the escape cone (shown as path ①) will escape from the module and is lost. The scattered light outside the escape cone can either be reflected back towards the cell-covered area ② or towards the backsheet area ③. The light that is reflected towards the backsheet area will be scattered once more.

three factors influence the amount of light that is scattered by the backsheet and is utilized by the solar cells: (1) the geometry of the backsheet area, (2) the spectral and (3) the angular backscattering properties of the backsheet. We propose a method to quantify the influence from the backsheet area on the short-circuit current of a PV module. To verify and test our model, light beam induce current (LBIC) measurements are used to characterize the amount of light scattered at the backsheet and utilized by the solar cells. The spectrum and angular backscattering properties of the backsheet are taken into account by fitting the LBIC measurement results at different wavelengths. Also, PV modules using halved cells are constructed and characterized.

2. Theory and method

2.1. Optical model for calculating the short circuit current increase

In order to analyse the reason for an increase of the short circuit current, a numerical model has been set up that allows simulating this effect. There are two options how the input parameters for the simulation can be obtained. First, based on the direct optical characterization of the backsheet the angle and spectral dependence of the back reflection is experimentally determined and used for the simulation. Second, the optical properties of the backsheet are determined indirectly by analysing a test sample, i.e. a one cell mini-module, using a LBIC set-up with various light sources. The underlying model and simulation approach will be described in this section while the experimental results are shown in Section 4.

In order to calculate the short circuit current contribution from the backsheet, an optical model is built. By using this model, the amount of light that reaches the backsheet area and is reflected back onto the area covered by solar cells can be compared with the amount of light that reaches the solar cells directly.

The model used in the present work is implemented in MATLAB [12], using the following assumptions:

1. The refractive indices of the glass and EVA are assumed to be equal, a discussion of which is described in Ref. [13]. Ref. [13] shows that the reflection at glass–EVA interface is below 0.01%, thus the assumption of equal refractive indices of the two materials is reasonable.
2. The thickness of the cell is ignored, and the cell and the backsheet are at the same height. Similar assumptions were used in Ref. [10]. For an industrial PV module, the thickness of the EVA layer is usually around 0.5 mm, thus there will be certain amount of light scattered to the rear side of the solar cell. We have briefly estimated the overestimation on the calculation result from this assumption. It is calculated that the EVA layer mainly affects the results for the backsheet area within 2 mm from the cell edge. The largest overestimation is around 1.6% relative. The height difference, therefore, is considered as a second order effect and has been neglected in the further study.
3. The quantum efficiency of the cells is independent from the incident angle of the radiation.
4. Due to the limit of the computation time, the reflections at the back sheet and the glass/air interface are calculated twice. After the second calculation, the remaining light on the backsheet area is considered to be lost. These losses account for around 0.6% of the total incident light.

The radiant power that directly reaches the cell can be represented by

$$P_{\mathrm{cell}}=\phi_{\mathrm{p}}A_{\mathrm{cell}}. \tag{1}$$

Here, ϕ_{p} is the power of the incident light that reaches the cell or backsheet per area and A_{cell} is the cell area.

Ray tracing is used to calculate the radiant power that is reflected by the backsheet area and reaches the solar cells. In the model, the full module is divided into unit elements, each with an area of 1 mm × 1 mm. Any unit element of the backsheet area scatters light into 3600 outgoing rays with a uniform separation of 6° azimuth angle and 3° polar angle.

The luminous flux of each ray is calculated by the following steps:

1) The scattering angle (θ) and wavelength (λ) dependence of the normalized reflected radiant intensity $S_{\mathrm{n}}(\theta,\lambda)$ and the direct reflectance $r(\lambda)$ are determined experimentally, which will be described in Section 3.1. $S_{\mathrm{n}}(\theta,\lambda)$ is obtained from normalizing the measured signal at a certain angle to the largest measured signal value.
2) The wave-length dependent irradiance at a certain direction and certain wavelength $S(\theta,\lambda)$ can be calculated by

$$S(\theta,\lambda)=A\phi_{\mathrm{p}}r(\lambda)\frac{S_{\mathrm{n}}(\theta,\lambda)}{\iint S_{\mathrm{n}}(\theta,\lambda)\sin(\theta)d\varphi\, d\theta}. \tag{2}$$

Fig. 2 shows a sketch of the situation described in Eq. (2). Here, A is the area of a unit element on the backsheet, ϕ_{p} is the total light power incidents on this area, θ is the angle between the scattered ray direction and the surface normal (polar angle) while φ is the azimuthal angle in the spherical coordinate system.

The pathway of the scattered rays inside the module is described in Fig. 3. If the incident angle of the ray is larger than the critical angle of total internal reflection, the ray is totally internally reflected. The refractive index of the PV module glass used in our experiments is kept fixed at $n=1.5$ and independent of wavelength, thus the corresponding critical angle is 41.8° [14]. If the incident angle is smaller than the critical angle, the reflectance and transmittance depend on the incident angle, and is calculated with the Fresnel equations [14]. In this simulation light is regarded