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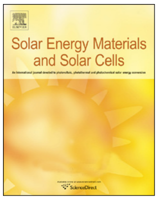

Systematic analysis of diffuse rear reflectors for enhanced light trapping in silicon solar cells

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ABSTRACT

Simple diffuse rear reflectors can enhance the light path length of weakly absorbed near infrared light in silicon solar cells and set a benchmark for more complex and expensive light trapping structures like dielectric gratings or plasmonic particles. We analyzed such simple diffuse rear reflectors systematically by optical and electrical measurements. We applied white paint, TiO_2 nanoparticles, white backsheets and a silver mirror to bifacial silicon solar cells and measured the enhancement of the external quantum efficiency for three different solar cell geometries: planar front and rear side, textured front and planar rear side, and textured front and rear side. We showed that an air-gap between the solar cell and the reflector decreases the absorption enhancement significantly, thus white paint and TiO_2 nanoparticles directly applied to the rear cell surface lead to the highest short circuit current density enhancements. The short circuit current density gains for a 200 μm thick planar solar cell reached up to 1.8 mA/cm^2, compared to a non-reflecting black rear side and up to 0.8 mA/cm^2 compared to a high-quality silver mirror rear side. For solar cells with textured front side the short circuit current density gains are in the range between 0.5 and 1.0 mA/cm^2 compared to a non-reflecting black rear side and do not significantly depend on the angular characteristic of the rear side reflector but mainly on its absolute reflectance.

1. Introduction

Light trapping in silicon solar cells is a key aspect for future efficiency increases and cost reductions. Due to the weak absorption of photons in the near infrared (NIR) between 900 and 1200 nm in crystalline silicon, structures that enhance the light path length have to be applied. At the front surface such a light path length enhancement can be reached by pyramidal front side textures, which also cause a significant reduction of reflection losses over the complete spectrum [1–4]. Light trapping can also be improved at the rear surface. Goetzberger [5] and Yablonovitch [6] described the improvement of a solar cell using a Lambertian rear reflector. Following this pioneering work, many devices have been realized using rather simple fabrication techniques. For example, Cotter et al. [7] investigated the optical intensity of light in layers of silicon with diffuse rear reflectors and deduced, that the refractive index of the diffuse reflector should be as high as possible. Berger et al. [8] investigated commercial white paint as a diffuse rear reflector. Applied to 1–2 μm thin-film polycrystalline silicon solar cells, they measured a short circuit current density gain of up to 2.87 mA/cm^2, which led to an overall J_{SC} of 9.91 mA/cm^2. Barugkin et al. [9] used Ag nanoparticles covered with a $BaSO_4$ based white paint as a rear reflector. They used a 260 μm thick solar cell with a reactive ion etched textured front side. They reached a J_{SC} of 5.7 mA/cm^2 between 990 and 1200 nm corresponding to a J_{SC} gain of 2.3 mA/cm^2 compared to solar cells with planar front and rear. Binders used in usual white paints are organic materials with a low refractive index (1.4–1.7), which absorb light [10] in the near infrared. Therefore, a binder-free, fully covered rough rear surface with a high refractive index is advantageous. Lee et al. [11] dispersed TiO_2 nanoparticles in deionized water with a pH value of 10 and deposited them via drop coating. With this method it is possible to cover the rear side with TiO_2 nanoparticles only. However, the alkalized suspension can harm the rear side of the solar cell. The TiO_2 nanoparticles were placed behind 2.5 μm thick crystalline silicon solar cells. They presented a ΔJ_{SC} of 3.91 mA/cm^2, which leads to an overall J_{SC} of 13.46 mA/cm^2. In comparison, Basch et al. [10] dispersed the TiO_2 nanoparticles in pH neutral water, which does no harm the solar cells. Additionally, the TiO_2 nanoparticles were compared with white paint and show an enhanced reflectivity [10]. The TiO_2 nanoparticles were placed behind 2 μm thick amorphous silicon cells. They presented a ΔJ_{SC} of 4.8 mA/cm^2, which leads to an overall J_{SC} of

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18.7 mA/cm^2. Ingenito et al. applied TiO_2 based white paint as rear reflectors for 180 μm thick, both side textured crystalline silicon solar cells and demonstrated a current density gain of 0.6 mA/cm^2 compared to no rear reflector [12]. For the deposition of TiO_2 particle layers also on large scale, methods are presented in literature using simple and scalable processes [13]. In [14] Frank et al. simulated the potential photocurrent density J_{ph} based on the measured properties of different diffuse rear reflectors for 200 μm thick silicon wafers with three different combinations of surface morphologies: planar front and rear surface (pp), textured front (random pyramids) and planar rear surface (tp), or both sides textured with random pyramids (tt). They compared white paint, polytetrafluoroethylene (PTFE), white paper and a silver mirror. One conclusion of the work of Frank et al. was the prediction that both-side textured solar cells with a good rear side reflector show the overall highest photocurrent density.

Furthermore, a large variety of more complex light trapping structures is reported in literature, including periodic gratings [15–21], metal structures utilizing plasmonic effects [22,23] or combinations of nanotextures and dielectric rear reflectors [24]. Bermel et al. showed that the absorption in thin film silicon solar cells can be enhanced by a relative amount of over 30% using photonic crystals [16]. Peters et al. [18] simulated a short circuit current density (J_{SC}) enhancement of 1.85 mA/cm^2 for a 40 μm thick silicon solar cell due to a diffractive grating on the rear side compared to a specular rear side. This leads to an overall efficiency increase of 1% and a total efficiency of 18.7%. Mellor et al. [25] predicted a J_{SC} enhancement of up to 1.5 mA/cm^2 for a 200 μm thick silicon solar cell with nanoimprinted diffraction gratings at the rear leading to an overall J_{SC} of 38 mA/cm^2. Tucher et al. [26] presented short circuit current density gains due to a diffractive rear side grating of up to 1.2 mA/cm^2 in 250 μm thick silicon solar cells with planar front side compared to a mirror on the rear side. Eisenlohr et al. [21] demonstrated a J_{SC} enhancement of 1.4 mA/cm^2 due to a sphere grating rear side (also compared to a mirror at the rear side) for 200 μm thick solar cells with planar front side.

Many of the experimental studies introduced above investigated one specific rear side reflector on one specific solar cell type and geometry. Hence it is difficult to compare the presented results quantitatively. Therefore, in this paper we present a systematic analysis of simple diffuse rear reflectors. We investigated different white backsheets, white paints and TiO_2 nanoparticles. For reference we also investigated a silver mirror and black cardboard as rear reflectors. Furthermore, we considered different surface geometries. Samples with planar front and rear were analyzed, because any light trapping effects caused by a diffuse rear reflector are most pronounced in such a structure. Samples with textured front and planar rear were included, as this configuration is widely used for high efficiency silicon solar cells [27]. Finally, both sides textured samples were considered, because the simulations of Frank et al. [14] suggested the highest current potential for these structures. Fig. 1 shows the principle structure of the measured systems with a diffuse rear reflector. We placed the white paint and TiO_2 nanoparticles directly on the rear side – no air gap remained. On the other hand we placed the backsheets and the mirror behind the rear side with a remaining air gap. The difference between the two setups is that in a) the light can be scattered into a broader angular range within the silicon while in b) due to refraction, scattered light is confined to a cone with an opening angle of about 16° within the silicon.

We analyzed the different direct and diffuse reflectivities of the used materials and measured the reflectance and transmittance of silicon wafers with all different reflectors to estimate the possible absorption enhancement. Finally, we tested the best rear reflectors on the device level. For this purpose we used bifacial solar cells originally optimized for experiments with upconverting materials at the rear side [28] and measured the external quantum efficiency (EQE) and the *IV*-curve for the different rear reflectors.

2. Materials and methods

For the optical and electrical measurements we placed different reflectors as summarized in Table 1 behind wafers and solar cells, respectively. Their reflectance measured in air is displayed in Fig. 2.

For dense, pin-hole free coverage, we applied three layers of white paint on the wafer with a bristle brush. The single layers were dried for 2 h at room temperature. For the TiO_2 coating we used a combination of the methods established by Basch et al. [10] and Lee et al. [11]. 10 g rutile TiO_2 nanoparticles were dispersed in 100 g purified water and the resulting suspension sonicated for 30 min. The silicon wafers were put onto a hot plate at a temperature of 60 °C where several drops of the suspension were applied onto the wafer for a fully covered rear surface. We repeated the coating process 5 times, with several minutes of drying in between.

For the *optical experiments*, we used 200 μm thick, shiny-etched, 0.8–1.2 Ω cm, (100)-oriented n-type float zone (FZ) silicon wafers, with three different combinations of surface morphologies: planar front and rear surface (pp), textured front surface with random pyramids and planar rear surface (tp), or both sides textured with random pyramids (tt). To calculate the absorptance $A = 1 - R - T$, the reflectance R and transmittance T were measured

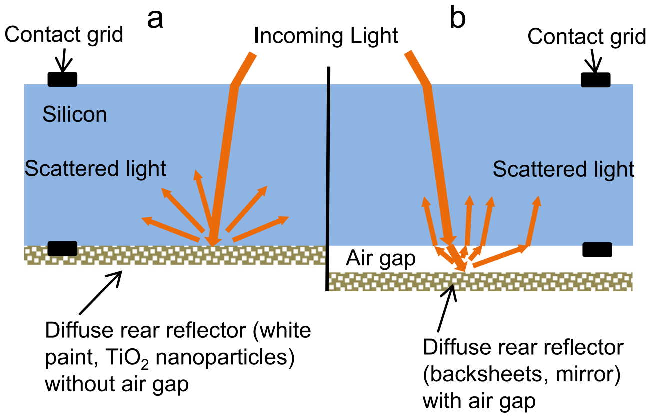

Fig. 1. Schematic structure of the measured system. It is possible to place the diffuse rear reflector behind the solar cell without (a) and with (b) an air gap.

Table 1
Used rear reflectors.

Air+Mirror	A silver mirror (Company: Thorlabs, reflectivity over 95% between 600 and 1400 nm) was placed behind the wafer while a gap of air remains between the wafer and the mirror
Air+Black cardboard	Black cardboard (reflectivity lower than 3%, transmission lower than 0.4% between 600 and 1400 nm) was placed behind the wafer while a gap of air remains between the wafer and the black cardboard.
Air+Backsheet	Three different white backsheets (Company: Isovoltaic, Material: 3554 and 2442w; Company: Dunmore, Material: PPE+) were located behind the wafer while an air gap remains between the wafer and the backsheets.
White paint	White paint was placed directly on the rear side of the wafer. (Company: OBI, Material: Premium white color; Company: Schöner Wohnen, Material: Polar white color; Company: Schmincke, Material: Acryl color, titanium white)
TiO_2 nanoparticles	TiO_2 nanoparticles with an average size of 1.106 μm were placed directly on the rear side of the solar cell precursors. Particles and method are described in Basch et al. [10]. (Company: Treibacher Industrie AG, Material: TiO_2-100, L32090)