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Bifacial multicrystalline silicon thin film solar cells

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ABSTRACT

Based on well-defined lab conditions, we have developed experimental methods to characterize bifacial laser crystallized multicrystalline silicon (mc-Si) thin film solar cells fabricated on glass. Key parameters which determine the performance of the bifacial solar cells such as light intensity and incidence angle dependence on both sides have been characterized. From these parameters and the local irradiance data, the annual power output of the bifacial solar cells can be simulated easily. In addition, bifacial measurements under well-defined conditions using a single sun simulator have been performed by means of a mirror. The best bifacial mc-Si thin film solar cell shows a "bifacial efficiency" of 12.4% compared to state of the art monofacial mc-Si thin film counterpart of 12.1%. According to our simulation, even a "bifacial efficiency" above 14% is realistic if the solar cell is installed in front of a white diffuse scattering surface with a reflectance of ~90%. A threshold of 24% additional light contribution at which the bifacial mc-Si thin film solar cells outperform the monofacial ones have been determined by simulations. This shows that the advantages of the bifacial cells can already be observed at very low level (< 25%) of additional reflected light contribution.

1. Introduction

Bifacial wafer solar cells can dramatically improve the power generation compared to monofacial cells [1], so they gain more and more attention in research. Up to now, bifacial wafer solar cells have been investigated intensively, and have been characterized mostly in the field with different backgrounds such as grass, concrete, soil, sand etc. These investigations show that upon 50% more power can be expected using the same effective area [1]. However, these investigations have been performed mostly under relatively undefined conditions such as local variation of albedo, non-uniform shadowing due to clouds etc. The output was usually presented as a "lump sum" of power gain measured within a certain time period. Such measurements were very time-consuming and unreliable, and they usually took several days up to years. In addition, the sampling under different installation angles and backgrounds was very limited, which can hardly provide sufficient information about the optimal conditions for installation. Bifacial thin film solar cells prepared on glass substrate have been intensively investigated in CIGS [2,3], transparent CdTe [4], Kesterites such as Cu_2ZnSnS_4 and $Cu_2ZnSnSe_4$ systems [5,6], perovskite [7] and SnS based solar cells [8], however, no studies have been performed on laser-crystallized multicrystalline Si (mc-Si) thin film solar cells prepared on glass substrate so far.

Basically, the performance of the bifacial solar cells originates from light intensity dependence and incidence angle dependence for both sides, and by the amount of additional reflected and scattered light from the background at the rear side. In order to know the precise properties of the bifacial solar cells, one would like to characterize both sides of the solar cells at well-defined conditions in the lab using a sun simulator. Particularly the light intensity and the incidence angle dependence are of great importance. So far, light intensity and incidence angle dependences have been separately investigated [9], no systematical ensemble investigations have been performed on bifacial solar cells, and no experimental bifacial measurements under well-defined conditions have been reported [10].

The bifacial concept can be applied to laser-crystallized mc-Si thin film solar cells as well. Thanks to the fast development in recent years [11–16], efficiencies exceeding 12% have been reached for mc-Si thin film solar cells fabricated on glass substrates [17,18]. The efficiencies reached in the mc-Si thin film solar cells are already close to their counterparts fabricated on mc-Si wafers with a thickness of ~200 μm. The absorber material used for the thin film solar cells (< 10 μm) is just a fraction of that of the wafer cells (< 4%). This grants the thin film mc-Si solar cells promising resource-efficiency and environmental compatibility for the future power supply. However, all the reported high efficiency mc-Si thin film solar cells are operated exclusively at monofacial mode, including a back reflector attached on the back side of the solar cells to harvest the long wavelength light transmitted through the absorber. No bifacial performance investigations on mc-Si thin film solar cells have been reported.

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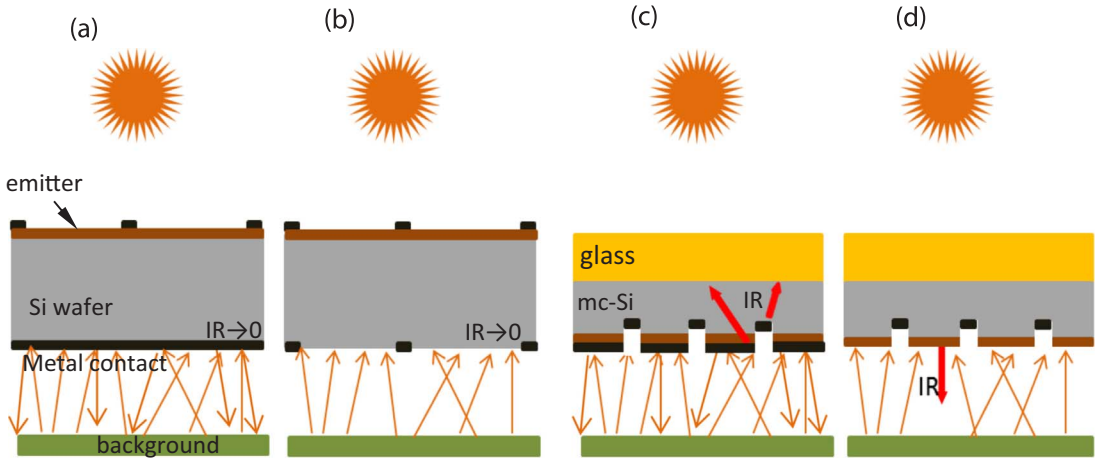

Fig. 1. Sketches of monofacial wafer cell (a), bifacial wafer cell (b), monofacial mc-Si thin film solar cell (c), and bifacial mc-Si thin film solar cell (d).

In case of the bifacial wafer cells, the advantage is quite obvious [19]. Almost all light with energy above the bandgap from the front side will be absorbed in the volume, and the transmitted infrared portion is against zero as illustrated in Fig. 1a. Any additional scattered and reflected light contribution from the back side will improve the power output of the bifacial wafer cell shown in Fig. 1b.

However, the situation for the mc-Si thin film solar cells is quite different. In the monofacial case of mc-Si thin film solar cells, a lot of the long wavelength IR light will be transmitted through the thin absorber and will be reflected back by the metal reflector to get reabsorbed in the absorber as illustrated in Fig. 1c. This transmitted IR light will be lost if no metal back reflector is used as sketched in Fig. 1d, so the power output or conversion efficiency will decrease at standard measurement conditions. However, the advantage of the bifacial mc-Si thin film solar cells is that they can harvest the scattered and reflected light from the background, and this contribution can compensate the loss due to the absence of a back reflector and even surpass the power output of the monofacial case if they are installed in front of a highly reflecting background. The overall effect is equivalent to solar cells with higher efficiencies operating under a monofacial mode. Therefore, the threshold upon which the bifacial cell outperforms the monofacial cell is the critical parameter determining if it makes sense to operate the mc-Si thin film solar cells in bifacial mode, and this aspect applies also to the above-mentioned bifacial thin film solar cells with other material system, so far no investigations have been done to determine the thresholds.

In this work, experimental methods have been developed to characterize the bifacial mc-Si thin film solar cells under well-defined conditions in the lab. These methods can be applied to bifacial wafer cells as well. mc-Si thin film solar cells in substrate and superstrate configurations have been investigated, with illumination from the emitter side or through the glass, respectively. First bifacial measurements have been performed under well-defined conditions using a single sun simulator by means of a mirror. By simulation, the thresholds at which the bifacial mc-Si thin film solar cells outperform the monofacial ones have been determined. The performance of the bifacial solar cells has been simulated at different levels of the rear side contribution in substrate and in superstrate configuration. Solar cells with an a-Si:H/c-Si heterojunction have been prepared on mc-Si thin films with and without nanowire texture, i.e., nanowire multiple core-shell solar cells [12,20] and planar solar cells [16]. The solar cells have been characterized under varying light intensities by means of neutral density (ND) filters, and different incidence angles by turning of the sample holder.

2. Method

The preparation of the samples is similar as described in Ref. [12]. Firstly, a-Si was deposited by electron beam evaporation onto Borofloat (Schott 33) glass substrates coated with an 80 nm SiN_x buffer layer. Doping of the layer was performed by heating a phosphorus source during a-Si deposition. The a-Si layer was crystallized by scanning the line focus beam of a high power cw diode laser (808 nm wavelength) at a rate of 1 cm/s. By this process the a-Si layer melts and solidifies to form grains up to several 100 μm perpendicular to the scan direction and several mm along the scan direction. The thickness of the layer is 8–9 μm with n-type doping of $\sim 1 \times 10^{17}$ cm^{-3}. After crystallization, the thin film was firstly dipped in 40% HF for several minutes to remove a silicon nitride containing surface layer. For drive-in of hydrogen atoms hydrogen passivation of the layer was performed using remote microwave plasma at a substrate temperature of 550 °C for 10 min. The gas mixture contains 80% hydrogen in argon at a flow rate of 10 sccm and at a constant pressure of 25 Pa.

After the hydrogen passivation, a dipping of the sample in 2% HF solution for 1 min was performed and the sample was cleaned with Piranha (H_2SO_4 (97%):H_2O_2 (30%) =1:1 by volume) at 80 °C for 15 min to remove organic and metallic contaminations on the surface. Then it was rinsed in deionized water and dried with N_2 blow.

For the preparation of the planar a-Si:H/c-Si heterojunction solar cells, a 200 nm topmost mc-Si layer has to be removed by an isotropic etching in a solution containing $KMnO_4$:HF(2%) with a weight ratio of 1:1000. This procedure is necessary to remove both, a layer damaged during the H-passivation and contaminants. Then the samples were rinsed with deionized water several times and cleaned with Piranha solution, followed by dipping in a buffered 2% HF to remove the oxide layer. After rinsing in ultrapure water (18.2 MΩ cm), the sample was immediately transferred into the PECVD chamber to deposit the a-Si:H emitter (10 nm intrinsic +20 nm highly p-type a-Si:H). The deposition of TCO is the same as in the nanowire case (see below). Mesa type solar cells have been prepared by the above-described procedure. The contact on the absorber is made by InGa alloy.

Silicon nanowires were etched by means of Ag-assisted wet chemical etching in a $AgNO_3$ (0.02 M): HF (5 M) solution at room temperature for 30 min, resulting in nanowires around 1 μm in length. The removal of the Ag contamination and treatment of the nanowires prior to the PECVD were described in detail elsewhere [12,21]. The sample was subsequently rinsed in ultrapure deionized water (18.2 MΩ cm), dried by N_2 blowing and was immediately placed into the PECVD chamber to deposit the a-Si:H shell layer. Deposition was performed at 225 °C. Thin intrinsic a-Si:H of ~2 nm was deposited prior to a highly doped p-type a-Si:H of ~5 nm. An ultrathin Al_2O_3 layer (~1 nm) is deposited followed by 200 nm aluminum doped ZnO (AZO) by atomic