EXPERIMENTAL STUDIES OF THE LIGHT TRAPPING AND OPTICAL LOSSES IN MICROCRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT

This study addresses the optimization of different optical components for the application in silicon thin-film solar cells. Decreasing the carrier concentration in the front contact has proven to significantly increase the quantum efficiency and the cell-current density. Besides that, an optically improved back reflector (employing an additional SiO_2 layer) and the optimized incoupling of light into the device (employing a refractive-index matching interlayer) was studied. In this contribution we show the potential of the different optical improvement possibilities as well as combinations thereof in order to obtain a maximized cell-current density in optically optimized solar cells. Limitations of the cell-current density are discussed with respect to theoretical calculations.

1. INTRODUCTION

Silicon thin-film solar cells are promising candidates for photovoltaic power generation in future. One approach employs hydrogenated amorphous silicon (a-Si:H) based active layers in single- or multi-junction solar cells. In superstrate configuration the cell is illuminated through transparent conductive oxide (TCO). Due to the intrinsically low absorbance of silicon in the long wavelength range, photon management is essential. The photon management comprises efficient coupling of light into the device as well as light trapping within the device. In general, the light trapping is achieved by combining front contact TCO with optimized properties as well as highly reflective back contacts. Besides being transparent and conductive, the TCO has to scatter the light efficiently. This is an important way to enhance light trapping inside the p-i-n device. However, there are still significant losses due to direct reflection of the light from the interface between TCO and silicon due to mismatch of refractive index and due to parasitic absorption of light in the front contact TCO especially in the near infrared (NIR) wavelength range.

In this contribution, we study the significance of different optical improvements. The influence of the front-contact parasitic absorption, the refractive-index matching at the front contact as well as an improved back reflector are studied in detail in microcrystalline silicon solar cells with intrinsic silicon thickness of 1 µm. The experimentally achieved quantum efficiency is compared to calculations based on theoretical models, especially based on the work of Deckman et al. [1]. Finally, the model is used to estimate the potential of cell-current density in the case that different optical improvement possibilities are combined.

2. EXPERIMENTAL

ZnO:Al films were prepared on Corning 1737 glass by rf magnetron sputtering from ceramic ZnO:Al_2O_3 target with 1 wt.% or 0.5 wt.% Al_2O_3, respectively. The approximately 800 nm thick, initially smooth films (root mean square (RMS) roughness about 15 nm) became surface-textured with typical RMS roughness of more than 125 nm by wet-chemical etching in diluted hydrochloric acid (0.5 % HCl). For refractive-index matching at the front contact additional TiO_2/ZnO layers were sputter deposited onto the etched ZnO:Al film with thicknesses of 50nm and 10nm, respectively. The back reflector was improved optically by introduction of a thermally evaporated SiO_2 layer with thickness of 50 nm between back-contact ZnO and evaporated silver. Details of film preparation and characterization are given elsewhere [2,3]. The light-trapping ability of a specific TCO film was characterized by application in solar cells. Microcrystalline silicon (µc-Si:H) layers were prepared using plasma-enhanced chemical vapor deposition at 13.56 MHz excitation frequency in a 30x30 cm^2 reactor. External quantum efficiency (*QE*) was measured by differential spectral response at zero bias. From spectral response measurement the short-circuit current density was estimated employing the AM1.5 solar spectrum. Henceforth this calculated current density is referred to as cell-current density.

3. RESULTS

Different individual optical improvements have been studied experimentally and are summarized in Table I. A reduction in front-contact carrier density was achieved by decreasing the target doping concentration from 1 wt.% to 0.5 wt.%. This increased the transmission of the front contact in the NIR spectral range considerably leading to an increase in cell-current density from 23.0 mA/cm^2 to 24.3 mA/cm^2 in case of an µc-Si:H solar cell with intrinsic silicon layer thickness ($d_{i\text{-}Si}$) of 1 µm [2]. The substrate temperature during sputter deposition had to be adjusted in order to maintain a surface topography after wet-chemical etching that is highly efficient for light scattering [2].

In case of improving the incoupling of light into the solar cell by introducing a TiO_2/ZnO bilayer between front-contact TCO and silicon, the cell-current density could be increased from 22.9 mA/cm^2 to 23.7 mA/cm^2 [3]. Finally, in case of an optically improved back reflector the cell-current density was increased from 22.9 mA/cm^2 to 23.7 mA/cm^2.

Table I. Cell-current density (in mA/cm^2) of µc-Si:H solar cells ($d_{i\text{-}Si}$ = 1 µm) in case of an increased front contact transmission, an additional refractive-index matching layer at the front contact and an optically optimized back contact, respectively.

optimization	reference	improved
front contact	23.0	24.3
refractive index	22.9	23.5
back contact	22.9	23.7

While in case of the optically optimized front-contact ZnO:Al the conversion efficiency of the solar cell improved, in case of the other optical improvements a deterioration of the electrical properties led to overall lower conversion efficiencies. Nevertheless, these experimentally achieved results illustrate the potential of further optical optimization.

Fig. 1 shows a measured *QE* (yellow area) and the corresponding total cell absorption (1-R_{cell}) of a µc-Si:H solar cell ($d_{i\text{-}Si}$ = 1 µm) with already improved front-contact ZnO:Al transparency (0.5 wt.% target doping concentration). Based on this the potential of further optical improvements was studied employing a theory by Deckman et al. [1] (see Fig. 1). Assuming a non-absorbing front contact, the cell-current density is estimated to posses an increase potential of 2.7 mA/cm^2 (red area in Fig. 1). An optimization of the back reflector (black) and the parasitic absorption in the doped silicon layers (grey) have a potential of 2.0 mA/cm^2 and 1.4 mA/cm^2, respectively. About 1.2 mA/cm^2 (green area) could not be unambiguously assigned to a loss mechanism, but is most likely due to reflection losses. A mismatch in refractive index is not considered by the theory of Deckman et al. and we found a considerable increase in the quantum efficiency in the spectral range 500 nm to 750 nm by introducing an antireflection coating between front-contact TCO and silicon (experiment summarized in Table I). Nevertheless, the most significant and (within the here studied light-trapping scheme) unavoidable fraction consists of primary (3.5 mA/cm^2) and secondary (8.4 mA/cm^2) reflection losses.

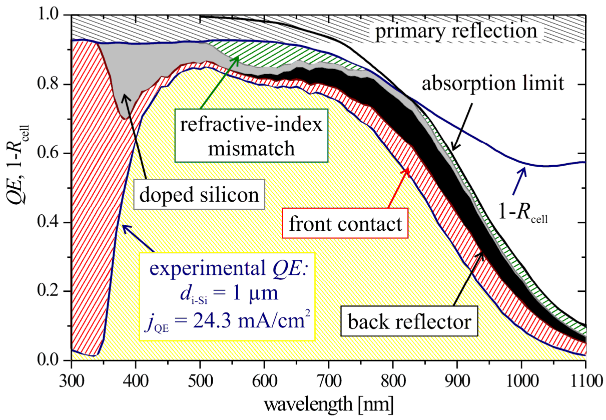

Fig. 1 Experimental *QE* and calculated optical improvements based on a theory of Deckman et al. [1].

The theory of Deckman et al. was applied to calculate a possible cell-current density by application of the individual optical improvements (Table I) at the same time combined with an antireflection coating of the glass substrate. Based on these assumption a cell-current density of about 27 mA/cm^2 ($d_{i\text{-}Si}$ = 1 µm) should be feasible.

4. CONCLUSIONS

Optically improved cell components were developed, and the application of the different individual optical improvements was studied experimentally in thin-film silicon solar cells. A combination of the optical improvements was studied based on calculations. In order to realize a cell-current density as high as 30 mA/cm^2, it is estimated that an intrinsic silicon layer thickness in the range of 2 µm to 2.5 µm will be needed.

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