29th European Photovoltaic Solar Energy Conference and Exhibition,
Amsterdam, the Netherlands, 22-26 September 2014

# ENHANCED LIGHT TRAPPING IN THIN FILM SILICON SOLAR CELLS BY ZINC OXIDE NANORODS

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ABSTRACT: In this contribution, the ZnO nanorods (NRs) are demonstrated as a very effective light scattering medium at the rear side of *nip* thin-film silicon solar cells grown on flexible stainless steel foil. After the implementation of the ZnO NRs, the Haze of the back reflector is increased by about 40% at almost all wavelengths from 300 nm to 1200 nm. The Haze increases up to about 90% over the entire visible wavelength regime after the ZnO NRs are coated with the back reflector consisting of Ag and aluminum doped zinc oxide (AZO). Even in comparison to a reference cell with a nano-imprinted replica of Asahi-U texture at the rear side, the application of the ZnO NRs in the hydrogenated amorphous silicon (a-Si:H) solar cell can lead to a $J_{sc}$ increase of 1.4 mA/cm$^2$ and an absolute efficiency increase of 0.72%

Keywords: a-Si:H, ZnO, nanorods, light trapping

## 1 INTRODUCTION

The thin-film solar cell is of particular interest due to the low material consumption and the ability of growing on flexible substrates. Among different kinds of thin-film solar cells, the hydrogenated amorphous silicon (a-Si:H) solar cell has an additional advantage of using an abundant material as the absorber layer. But there has been always a tradeoff in the optimization of a-Si:H solar cells: on the one hand, the thickness of the absorber layer is preferred to be as small as possible in order to reduce the influence of the small mean free path of carriers and light induced degradation, and to decrease the process and material cost. On the other hand, the short-circuit current density ($J_{sc}$) of the solar cell will drop with the thickness, decreasing the cell efficiency. In order to achieve high $J_{sc}$ with an absorber layer as thin as possible, effective light trapping is crucial. Many light trapping approaches, which include random [1] and periodic textures [2], and plasmonic nanoparticles [3], have been studied worldwide. In addition, growth of a-Si:H solar cells on nanostructures, such as nanorods [4, 5, 6, 7] and nanowires [8], has attracted a lot of attention, in particular because of the prospect of orthogonalization of the light propagation path and the carrier collection path [9]. However, it often happens that those nanostructures increase the $J_{sc}$ of the solar cell but decrease the $V_{oc}$ and FF. In this contribution, the ZnO nanorods (NRs) prepared by an electrochemical process are implemented in the *nip* a-Si:H solar cell on flexible stainless steel (SS) foil, aiming at increasing the $J_{sc}$ without deteriorate the $V_{oc}$ and FF.

## 2 EXPERIMENTAL

The thin film *nip* a-Si:H solar cells studied in this work are prepared on flexible SS foil. The a-Si:H layers are deposited by radio frequency plasma enhanced chemical vapor deposition (RF-PECVD), the AZO and Ag back reflector and the tin doped indium oxide (ITO) by RF-sputtering, and the Ag grid by e-beam evaporation. The basic or reference structure of the *nip* a-Si:H solar cell used in this work is SS/back reflector (BR)/n-type a-Si:H/intrinsic a-Si:H/p-type μc-Si:H/ITO/Ag grid. The thickness of the intrinsic a-Si is 250 nm. The BR consists of a stack of Ag and AZO, with thicknesses of respectively 300 and 80 nm. In addition to the components of the basic cell structure, there is the scattering medium consisting of either a nano-imprinted replica of Asahi-U texture or ZnO NRs. The type and location of the scattering medium will be specified later together with the results. The ZnO NRs are prepared by means of an electrochemical process which is in more detail described in other publications [10, 11].

For characterization, an AFM of Park NX-10 is used to investigate the morphology of ZnO NRs. Diffuse and integral reflectance are measured with Agilent Cary 500 to calculate the Haze spectrum resulting from different scattering media. The *J-V* characteristics of the solar cell is measured with a calibrated solar simulator under AM1.5 100 mW/cm$^2$ conditions (Wacom) and the spectral reponse is characterized with an Optosolar setup to determine the EQE .

## 3 RESULTS AND DISCUSSION

### 3.1 Morphology

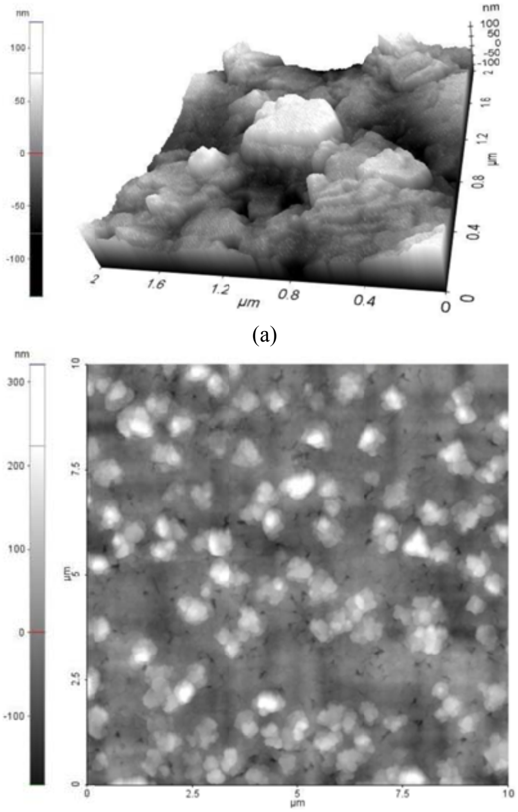
In order to investigate their scattering effect, ZnO NRs are prepared on the AZO of the BR that is directly on SS. AFM is used to investigate the morphology of the ZnO NRs. Fig. 1(a) shows the AFM image of a single ZnO NR in the center and the size of the single ZnO NR is about 400 nm × 400 nm × 200 nm. Fig. 1(b) shows the distribution of ZnO NRs, which appears very random, in a larger scan area.

### 3.2 Light scattering property

To quantify the scattering property of a scattering medium, Haze is defined by the equation:

$$\mathrm{Haze} = \frac{R_\mathrm{d}}{R_\mathrm{d}+R_\mathrm{s}}, \qquad (1)$$

where $R_\mathrm{d}$ is the diffuse reflectance and $R_\mathrm{s}$ is the specular reflectance. Fig. 2(a) shows the light scattering properties of the substrate which contains only the SS foil with the BR (untextured Ag/AZO) on top as a reference. Since the SS foil underwent several rolling processes, it is not completely flat but has its own roughness. Therefore, there is a certain Haze although it is relatively low. After the growth of the ZnO NRs on top of the AZO of the BR, there is significant enhancement of the diffuse reflectance and Haze as shown in Fig. 2(b). Since the ZnO NRs are not doped, there could be a problem of carrier transport due to their high resistivity. Therefore, another substrate is prepared. On top of the stack SS/Ag/ZnO/ZnO NRs, another Ag/ZnO BR is grown, which serves as the real back contact, is grown. In this way, the ZnO NRs are only used morphologically as a light scattering medium but cannot electrically influence the solar cell. The substrate shows very high Haze of over 90% in the entire spectral range (Fig. 2(c)). For comparison, the nano-imprinted replica of Asahi-U texture is applied to SS as the scattering medium before the BR is deposited, and the corresponding reflectance and Haze are shown in Fig. 2(d). In this case, the nano-imprinted replica of Asahi-U texture results in a lower Haze than the sample with ZnO NRs corresponding to Fig. 2(c).



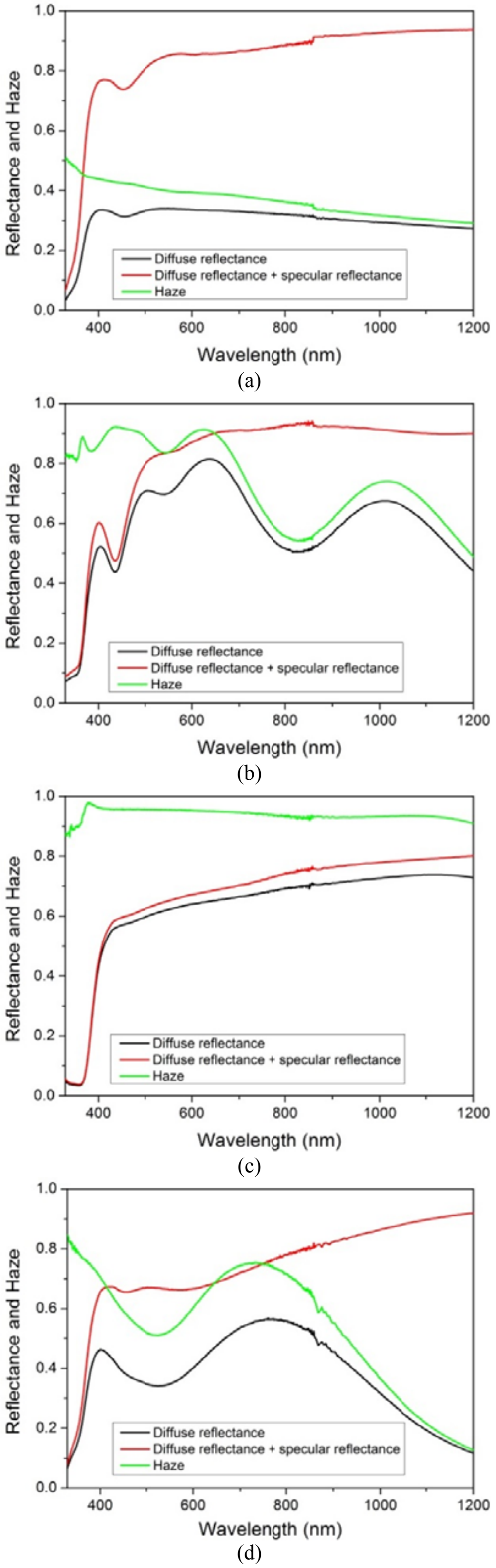
(a)

(b)

**Figure 1:** AFM image of ZnO NRs in the scan area of (a) 2 µm × 2 µm and (b) 10 µm × 10 µm

3.3 Solar cell performance

After the same a-Si:H, ITO and Ag grids are deposited side by side on those four kinds of samples shown in Fig. 2, the complete solar cells are characterized and the results are listed in Table I. It can be easily understood that the BR directly on SS leads to the lowest $J_{sc}$ since the Haze is low. By implementing the ZnO NRs into the solar cell, the $J_{sc}$ is increased by 2 mA/cm$^2$. Since the ZnO NRs are not doped and thereby very resistive, the *J*-*V* curve of the solar cell of No. 2 with a-Si:H grown directly on ZnO NRs, leading to low FF and $V_{oc}$ shows an electrical barrier (S-shape *J*-*V* cruve). When the ZnO



(a)

(b)

(c)

(d)

**Figure 2:** The reflectance measurement as well as the Haze factor for (a) the substrates with the structures of (a)

SS/BR, (b) SS/BR/NRs, (c) SS/BR/NRs/BR and (d) SS/nano-imprinted replica of Asahi-U texture/BR

NRs are coated with Ag and AZO, the solar cell shows 2.4 mA/cm$^2$ higher $J_{sc}$ than the reference cell of No.1 and 1.4 mA/cm$^2$ higher $J_{sc}$ than the cell of No. 4 with the nano-imprinted replica of Asahi-U texture, without deterioration of the $V_{oc}$ and FF. The optical enhancement of the solar cell by ZnO NRs is explicitly demonstrated in the EQE spectra of Fig 3. The ZnO NRs can enhance the EQE response in the wavelength range from 400 nm to 800 nm.

**Table I:** *J-V* characteristics of the solar cells with different scattering media. The external parameters of each sample are the average of the four best cells of a batch 26 cells with the area of 4x4 mm$^2$. The $J_{sc}$ is calibrated by the EQE measurement. The absorber layer is 250 nm thick

| No. | Substrate structure | $V_{oc}$ (mV) | $J_{sc}$ (mA/cm$^2$) | FF | Eff. |
|---|---|---|---|---|---|
| 1 | SS/BR | 857 | 11.4 | 0.616 | 6.02% |
| 2 | SS/BR/NRs | 803 | 13.4 | 0.475 | 5.11% |
| 3 | SS/BR/NRs/BR | 850 | 13.8 | 0.621 | 7.28% |
| 4 | SS/Replica of Asahi-U texture/BR | 851 | 12.4 | 0.622 | 6.56% |

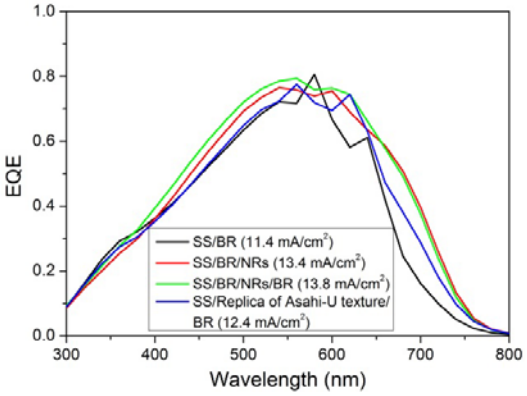


**Figure 3:** EQE spectra of a-Si:H solar cells with different textures

## 4 CONCLUSION

ZnO NRs prepared electrochemically on sputtered AZO are implemented into the rear of the *nip* a-Si:H solar cell grown on flexible SS foil. The SS substrate with the ZnO NRs combining with the BR shows very high Haze. The $J_{sc}$ of the solar cell with ZnO NRs is 2.4 mA/cm$^2$ higher than that of the cell without ZnO NRs. Even in comparison to the cell with nano-imprinted replica of Asahi-U texture, the $J_{sc}$ gain can be 1.4 mA/cm$^2$. Furthermore, there is no deterioration of the $V_{oc}$ and FF for the cell with ZnO NRs when the BR is deposited on top of ZnO NRs.

## ACKNOWLEDGEMENT

This work was funded by the European FP7 project, NanoPV (GA No. 246331).

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