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## Improved light management in silicon heterojunction solar cells by application of a ZnO nanorod antireflective layer

Maike Ahrlich\*, Oleg Sergeev, Maren Juilfs, Alex Neumüller, Martin Vehse, Carsten Agert

*NEXT ENERGY, EWE Research Centre for Energy Technology at the University of Oldenburg,  
Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany*

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### Abstract

This study reports successful application of ZnO nanorod arrays for efficient reduction of reflection losses in heterojunction solar cells on flat non-textured silicon wafers. In addition, aluminium doped zinc oxide (AZO) is proposed as a cheap, abundant and environment-friendly substitution for indium doped tin oxide (ITO), commonly used in transparent front electrodes. The results show a significant reduction of the average weighted cell reflectivity and hence an enhancement in the external quantum efficiency and in the short circuit current density. The main antireflective mechanism was found to be a grading of the refractive index at the AZO/air interface, which has been shown by optical simulations describing the nanorod layer as an effective medium.

The ZnO nanorod layers were grown by electrochemical deposition, which is a low-cost and industrially applicable method, since no vacuum conditions and high temperatures are required. Therefore, this concept could be a promising process step in the photovoltaic industry to improve light management in silicon heterojunction solar cells with AZO front contacts, especially attractive for the production utilizing very thin wafers, where wafer texturing for antireflection purposes shows important drawbacks.

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\* Corresponding author. Tel.: +49-441-99906-228; fax: +49-441-99906-109.

E-mail address: [maike.ahrlich@next-energy.de](mailto:maike.ahrlich@next-energy.de)

## 1. Introduction

The silicon heterojunction (SHJ) solar cell technology is attracting more and more attention in both photovoltaic research and industry due to its high efficiency, low temperature fabrication process and potentially lower production cost compared to the diffused homojunction crystalline silicon solar cell [1]. As for the case of homojunction silicon solar cells, the reflection losses in heterojunction solar cells need to be minimized in order to achieve higher energy conversion efficiency. From the other side, the performance of a SHJ solar cell is largely determined by the recombination losses on defects of silicon wafer surfaces.

A standard method to reduce reflection losses in SHJ solar cells is the use of pyramid-like textured wafer surfaces. However, wafer surface texturing is a rather complicated procedure which has several drawbacks. First of all, texturing affects electrical properties as it increases the overall surface area, and thus surface recombination losses will be higher. The textured wafer surface often shows numerous imperfections such as cracks, residuals of etchants and cleaning solvents which are very hard to remove. All of them are increasing defect density at the interface between silicon wafer and passivation layers. Moreover, texturing requires additional post-treatment, such as smoothing of the pyramids, since too sharp textured features can cause short circuits [2]. Besides, the fabrication of contact grids on highly textured surface with screen printing is also challenging due to the gapping between the screen and the texture.

Most commonly, wet chemical etching using KOH (potassium hydroxide), NaOH (sodium hydroxide) or TMAH (trimethyl ammonium hydroxide) is used for texturing [3,4]. However, this kind of texturing is only applicable for silicon wafers oriented in the  $\langle 100 \rangle$  crystallographic direction, which limits the choice for production. Furthermore, the SHJ solar cell technology is progressing towards very thin wafers ( $< 90 \mu\text{m}$  thickness), where wafer texturing could be hard to realize. Therefore, in this study, we introduce an alternative way to reduce reflection in SHJ solar cells on flat non-textured wafers.

One way to reduce reflection in flat solar cells is the application of a quarter wavelength antireflection coating [5,6,7]. In SHJ solar cells, with tin doped indium oxide (ITO) as common transparent front contact, the ITO thickness is adapted between 80 nm and 95 nm to minimize the reflection loss [7]. However, these conventional antireflection coatings only can achieve a low reflectance at a certain spectral range. For incident wavelengths out of this designed range, the measured reflection is considerably increased.

During the last years, zinc oxide (ZnO) nanostructure arrays were deposited as broadband antireflective coatings on top of silicon wafer solar cells [8], CIGS solar cells [9] and silicon thin-film solar cells in n-i-p configuration [10]. In general, the size of such nanostructures is smaller than the optical wavelengths of incident solar light, thus the light cannot resolve the individual nanostructure of the ensemble. The ensemble of these nanostructures therefore provides a continuous gradient of refractive index from their tops to the semiconductor material, which decreases the surface reflection [11]. This ZnO nanorod concept has already been applied to planar SHJ solar cells: by formation of a ZnO nanorod layer on top of the ITO front contact, the short circuit current density could be enhanced from  $29.0 \text{ mA/cm}^2$  to  $30.2 \text{ mA/cm}^2$  [12]. However, ITO has several significant disadvantages. First of all, the costs of ITO are very high, mainly due to the scarcity of indium [13]. Another issue is the toxicity of indium [14], possibly causing ITO to be a toxic compound as well. Replacing ITO with an abundant and environment-friendly material like aluminium doped zinc oxide (AZO) is hence highly relevant for the further development of cheap SHJ solar cells with less environmental impact.

Therefore, in this work, the antireflective properties of ZnO nanorod arrays implemented in silicon heterojunction solar cells with front contacts based on AZO were investigated. For the fabrication of ZnO nanorod arrays, electrochemical deposition was used as a low-cost and industrially applicable method.

## 2. Experimental

A schematic illustration of the SHJ solar cells used in this work is shown in Fig. 1. N-type double-side polished float zone c-Si wafers with  $\langle 100 \rangle$  surface orientation, a thickness of  $250 \mu\text{m}$  and a resistivity of  $1\text{--}5 \Omega\text{cm}$  were used as non-textured substrates. Prior to deposition, the substrates were immersed in hydrofluoric acid (1 %) for 3 min to remove the native oxide. The intrinsic and doped a-Si:H and  $\mu\text{c-Si:H}$  layers were deposited by plasma enhanced chemical vapour deposition from  $\text{SiH}_4\text{:H}_2$  mixture, adding  $\text{B}_2\text{H}_6$  or  $\text{PH}_3$  for p- and n-doping, respectively. The

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