Simulation-Based Analysis of Plasmonic Light Trapping in Thin-Film Silicon Solar Cells

Ulrich W. Paetzold, K. Bittkau, M. Meier, R. Carius and U. Rau
Forschungszentrum Jülich GmbH
IEK-5 Photovoltaics, 52425 Jülich, Germany
u.paetzold@fz-juelich.de

***Abstract*— We summarize on two examples of simulation-based analyses of light trapping in prototype thin-film silicon solar cells with plasmonic back contacts. First, based on optical simulations, the plasmon-induced light scattering at Ag back contact with non-ordered nanostructures is explained. Second, optical simulations of solar cells with plasmonic reflection-grating back contacts are presented. The simulated and measured spectral response of these solar cells agree very well, allowing an optimization of the nanostructures and an in-depth analysis of the light-trapping.**

I. Introduction

Light trapping is essential for thin-film silicon solar cells made of amorphous (a-Si:H) and microcrystalline silicon (µc-Si:H). In order to increase the absorption of light in the optically thin silicon absorber layers, incident light is scattered and diffracted such that the effective light path in the silicon layers is enhanced. Conventional thin-film silicon solar cells apply randomly textured front and back contacts to scatter incident light into the silicon absorber layers. Alternatively, novel light-trapping concepts, which apply localized surface plasmon induced light scattering at Ag nanostructures have been suggested to exceed the conventional light trapping [1,2].

Localized surface plasmons (LSP) denote coherent collective oscillations of the free electron gas in nanostructures [3]. At Ag nanoparticles or nanostructured Ag layers, light can couple efficiently to LSP resonances. For certain geometries, the radiative decay of these oscillations causes a very efficient scattering of the incident light. Making use of this effect, Ag nanostructures which exhibit LSPs can serve as sub-wavelength scattering components that couple incident light into the silicon absorber layers of a solar cell [1,2,4-9].

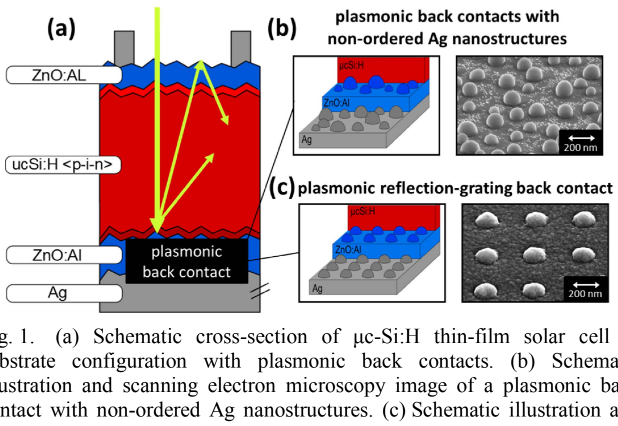

Fig. 1. (a) Schematic cross-section of µc-Si:H thin-film solar cell in substrate configuration with plasmonic back contacts. (b) Schematic illustration and scanning electron microscopy image of a plasmonic back contact with non-ordered Ag nanostructures. (c) Schematic illustration and scanning electron microscopy image of a plasmonic reflection-grating back contact with periodically arranged Ag nanostructures.

In this contribution, we summarize on our prototype thin-film silicon solar cells with plasmonic back contacts and the simulation-based analyses of the light trapping in these solar cells. Plasmonic back contacts with non-ordered Ag nanostructures (see Fig. 1 (b)) and ordered Ag nanostructures, called plasmonic reflection-grating back contacts (see Fig. 1 (c)), are studied. These back contacts were designed for the application in µc-Si:H thin-film solar cells [7]. Three-dimensional electromagnetic simulations were applied to study the interaction of light with the plasmonic back contacts in the solar cells. The simulations were conducted with the program JCMsuite (JCMWave GmbH, Berlin).

I. Back Contacts with Non-Ordered Nanostructures

A simple way for the fabrication of non-ordered plasmonic nanostructures on Ag back contacts is presented in [6]. Non-ordered Ag nanoparticle distributions, prepared by thermally induced agglomeration of Ag films, were coated with Ag and ZnO:Al. Variations of the initial size distribution of the Ag nanoparticles resulted in back contacts with various Ag nanostructure distributions. The distribution of the Ag nanostructures was characterized by atomic force microscopy (see Fig. 2 (b)). A µc-Si:H solar cell in substrate configuration prepared on such back contact (Type D in Fig. 2 (d)) showed a significantly enhanced external quantum efficiency (EQE). i.e. enhanced light-trapping effect, for wavelengths longer than 500 nm when compared with a flat solar cell [6].

In order to analyze the light-scattering of the nanostructured back contacts, three-dimensional electromagnetic simulations were applied [6]. Prior to the deposition of the µc-Si:H solar cell the diffuse reflectance spectra of the back contacts with non-ordered Ag nanostructures were measured (see Fig. 2 (c)). These measured reflectance spectra are compared with reflectance spectra calculated as a superposition of simulated reflectance spectra of LSP resonances in isolated Ag nanostructures at the back contact (see Fig. 2 (d)). With increasing size of the nanostructures (from Type A to Type E), the measured and simulated diffuse reflectance increases and the maximum shifts to longer wavelengths. Due to the qualitatively good agreement between the measured and simulated reflectance spectra for various types of Ag back contacts with non-ordered nanostructures, the enhanced diffuse reflectance is attributed to LSP-induced light scattering. Thus, based on the simulations, the light-trapping of the prototype solar cell presented in [6] can be associated clearly to LSP-induced light-scattering at the back contact.

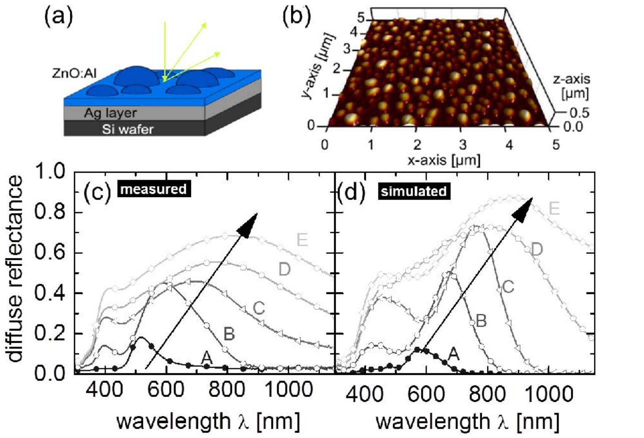

Fig. 2. (a) Back contact with non-ordered Ag nanostructures. (b) Atomic force microscopy image of the surface topography (type C). (c) Measured and (d) simulated diffuse reflectance, of five types of Ag back contacts with various distributions of non-ordered nanostructures. The mean size of the nanostructures increases from type A to type E (for details see [6]).

II. PLASMONIC REFLECTION-GRATING BACK CONTACTS

The plasmonic reflection-grating back contact consists of Ag nanostructures arranged in square lattice at the back contact of a thin-film silicon solar cell (see Fig. 1(c)). Experimental results of prototypes of µc-Si:H thin-film solar cells in substrate configuration showed significantly enhanced EQE, i.e. short-circuit current density, when compared to flat solar cells [7]. For an optimized period of the plasmonic reflection-grating back contact, even a small enhancement of the short-circuit current density in comparison to the reference solar cells, applying the random light-trapping texture, was measured. Within the perspective of geometrical optics, the light trapping which is induced by plasmonic reflection-grating back contacts is explained by an enhancement of the light path in the µc-Si:H absorber material [7]. This enhancement of the light path is caused by the diffraction of incident light at the back contact beyond the total internal reflection angle of the µc-Si:H/air interface which results in long effective light paths of the light scattered at the back contact.

The light trapping in the solar cells with plasmonic reflection-grating back contacts was further investigated with optical simulations. Therefore, the interaction of an incident electromagnetic wave and the layer stack of solar cell was simulated with 3D electromagnetic simulations. The simulated electric fields in the solar cell exhibit a three-dimensional pattern (see Fig. 3 (a)). In the perspective of geometrical optics, this pattern is explained as a superposition of the light scattered at the back contact and the light reflected back from the front interface. An alternative terminology of the multiple internal reflection of the light in the solar cell layer stack is the coupling of light, via the plasmonic reflection grating back contacts, into guided modes which are supported by the high refractive index µc-Si:H layers of the solar cell. The excitation of these guided modes is resonant and can be observed as resonances in the simulated *EQE* of the solar cell (see Fig. 3 (b)). In a previous publication, the authors demonstrated a very good agreement between the simulated and measured *EQE* of the solar cells when taking experimental variations into account [9]. Based on this agreement, the geometry of the plasmonic back contact can be optimized in further.

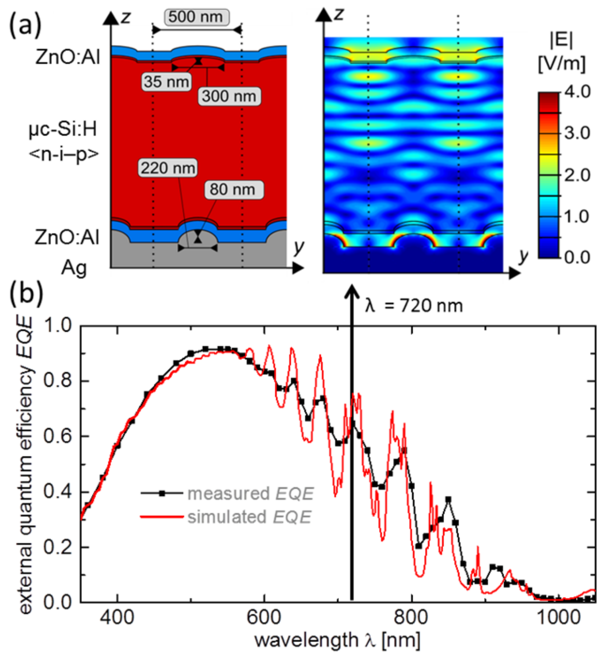

Fig. 3. (a) Schematic cross section and simulated electric field distribution of a cross-section of µc-Si:H solar cell with plasmonic reflection grating back contact. (b) Measured (black) and simulated (red) external quantum efficiency (EQE) of a µc-Si:H solar cell in substrate configuration deposited on a plasmonic reflection grating back contact of period of 500 nm [9].

ACKNOWLEDGMENT

The authors acknowledge the discussions with E. Moulin, B. Pieters, T. Merdzhanova, M. Ermes, A. Hoffmann, F. Finger, V. Smirnov, D. Michaelis, C. Wächter, V. Hageman.

REFERENCES

[1] K. B. Catchpole and A. Polman, "Plasmonic solar cells," Appl. Phys. Lett., vol. 93, 191113 2008.

[2] H. A. Atwater and A. Polman, "Plasmonics for improved photovoltaic devices," Nat. Mat., vol. 9, pp.205–213, 2010.

[3] U. Kreibig and M. Vollmer, Optical Properties of Metal Clusters. Springer-Verlag, Berlin, 1995.

[4] S. Fahr, C. Rockstuhl, and F. Lederer, "Photonic crystal intermediate reflector in micromorph tandem solar cells," Appl. Phys. Lett., vol. 95, 121105, 2009.

[5] V. E. Ferry, M. A. Verschuuren, H. B. T. Li, E.Verhagen, R. J. Walters, R. E. I. Schropp, H. A. Atwater, and A. Polman et al., "Light-trapping in ultrathin photovoltaic devices," Opt. Express vol. 18, pp. 102, 2010.

[6] U. W. Paetzold, M. Meier, E. Moulin, V. Smirnov, B. E. Pieters, U. Rau, and R. Carius, "Plasmonic back contacts with non-ordered Ag nanostructures for light trapping in thin-film silicon solar cells" Materials Science and Engineering B, vol. 178, 630–634, 2013.

[7] U. W. Paetzold, E. Moulin, B. E. Pieters, R. Carius, and U. Rau, "Design of nanostructured plasmonic back contacts for thin-film silicon solar cells," Opt. Express, vol. 19, 1219, 2011.

[8] U. W. Paetzold, E. Moulin, D. Michaelis, W. Bottler, C. Wachter, V. Hagemann, M. Meier, R. Carius, and U. Rau, "Plasmonic reflection grating back contacts for microcrystalline silicon solar cells," Appl. Phys. Lett., vol. 99, 181105, 2011.

[9] U. W. Paetzold, E. Moulin, B. E. Pieters, U. Rau, and R. Carius, "Optical simulations of microcrystalline silicon solar cells applying plasmonic reflection grating back contacts," J. Photon. Energy, vol. 2, 027002, 2012.