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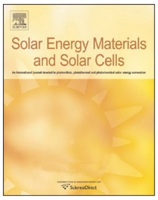

Rear side sphere gratings for improved light trapping in crystalline silicon single junction and silicon-based tandem solar cells

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ABSTRACT

Rear side hexagonal sphere gratings are demonstrated as diffractive structures that enhance the light path length in the near infrared, where crystalline silicon solar cells suffer from weak absorption. Moreover, the rear side sphere grating can be added behind a solar cell with flat rear surface, giving an "electrically flat but optically rough" device with high efficiency potential. Here, a thin passivating tunnel-contact layer electrically separates the sphere grating from the cell's base. Solar cells with the rear side sphere grating have obtained a V_{OC} of up to 710 mV and a FF of up to 81.9%. External quantum efficiency measurements show a current density gain of 1.4 mA/cm^2 due to the sphere grating. This leads to an overall efficiency of up to 22.1% for the solar cells with planar front side and rear side sphere grating. Estimates for perovskite–silicon and III/V-silicon tandem devices show that the efficiency of tandems can be enhanced by up to 2.4% absolute with a sphere grating on the rear side. Thus, sphere gratings could improve Si-based tandem devices that are limited due to a low current in the Si bottom cell.

1. Introduction

Periodic dielectric nanostructures at the rear side of crystalline silicon solar cells can enhance the path length of near infrared light in the weakly absorbing silicon bulk material. The use of diffractive gratings at the rear side of solar cells was proposed by Heine and Morf [1]. In the last two decades numerous theoretical and simulation-based investigations indicated that diffractive structures can achieve efficient light trapping and hence a photocurrent density gain in crystalline silicon solar cells [2–9]. Light trapping enhancements due to diffractive structures have also been investigated (e.g. [10–13]) and shown experimentally (e.g. [14,15]) in thin-film silicon cells. For wafer based crystalline silicon solar cells there are experimental results published currently with nano-imprinted rear side gratings [16]. Especially for thinner silicon solar cells such novel light trapping concepts are essential. The optimum cell thickness of crystalline silicon solar cells for approaching the fundamental Auger limit lies in the range of 100 μm [17] – a thickness where improved light trapping is required.

Furthermore, rear side light trapping structures are promising for emerging silicon based tandem solar cells. The silicon bottom solar cell can only utilize the longer-wavelength part of the spectrum, which is weakly absorbed in silicon, thus necessitating efficient light trapping. Additionally, in many tandem concepts, for example wafer bonding [18] or direct III/V growth [19], the front side of the silicon cell is required to be planar and all the light trapping has to be realized at the rear. Silicon based tandem solar cells have been reported that are current-limited by the silicon cell [18,20–22]. Enhancing the current of the silicon cell will improve the current matching, thus leading to an overall higher current and efficiency.

The approach presented in this paper is a sphere grating consisting of hexagonally ordered monodisperse spheres with a low refractive index embedded in a high refractive index matrix. The refractive index contrast between the spheres and the matrix material creates a diffractive structure. Absorption enhancement in crystalline silicon wafers due to a sphere grating has already been reported [23]. In this work, we integrate the sphere gratings into fully processed silicon solar cells. As depicted in Fig. 1, we aim

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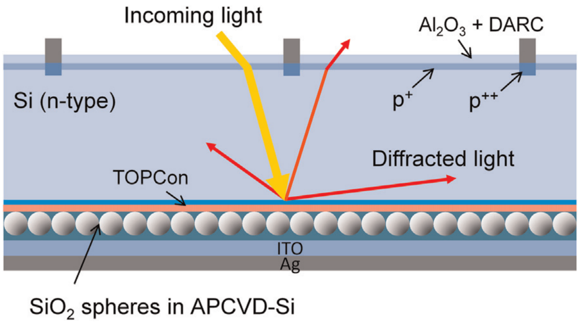

Fig. 1. Schematic sketch of the concept of the proposed rear side structure. The rear optics is electrically separated from the cell's base by a thin TOPCon passivation. Incoming light is redirected into shallow angles by the rear side sphere grating in order to enhance the absorption in the near infrared.

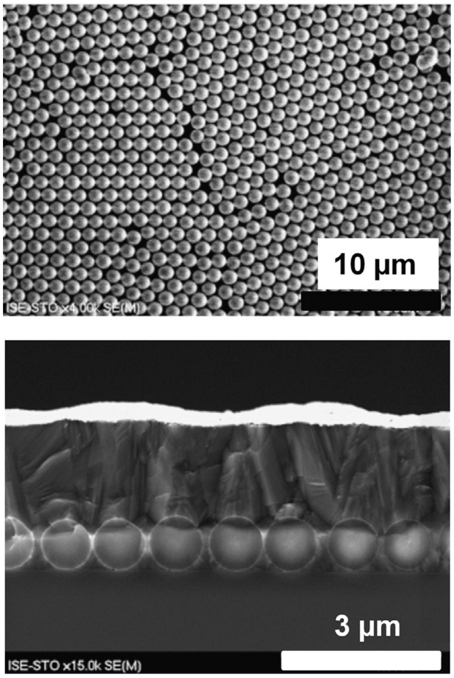

Fig. 2. Two SEM pictures of the sphere grating. The upper one shows a top view of the hexagonally ordered spheres after spin coating, the lower one a cross-section after APCVD of the matrix.

for a solar cell with electrically flat, but optically rough surfaces – meaning that the device's electrical boundaries are planar, and its optical texture comes from structures outside the electrically-active base of the cell. This allows us to simultaneously achieve high voltages due to low surface recombination and high currents from light trapping. The electrical separation between the cell's base and the rear optics is accomplished by a thin passivation layer, specifically a tunnel oxide passivated contact (TOPCon) consisting of a tunnel oxide layer and a doped silicon layer at the rear side. Silicon solar cells featuring such a TOPCon rear side structure already demonstrated very high efficiencies of up to 24.4% [24]. Integrating sphere gratings into a solar cell with TOPCon rear side features three challenges: the near infrared absorption has to be enhanced, the excellent passivation quality has to be maintained, and a low contact resistance through the whole structure has to be realized. By showing the compatibility of the sphere grating fabrication with high voltages, high fill factors and an enhanced current density we demonstrate that the gain predicted by theory and simulation can be verified on the device level.

2. Experimental

For all experiments with solar cells and solar cell precursors, shiny-etched, 1 Ω cm, (100)-oriented n-type FZ silicon wafers with 200 µm thickness have been used. The tunnel oxide passivated contact (TOPCon) has been realized according to [25,26]: a 1.4 nm thin tunnel oxide is grown in nitric acid and a 20 nm thin phosphorous-doped Si-layer is deposited by plasma enhanced chemical vapor deposition (PECVD). Following deposition, the samples are annealed in a tube furnace at 800 °C. The fabrication of the sphere grating has been done similar to [23,27]. For this work we adapted the sphere grating fabrication for the TOPCon surface. We used commercially available monodisperse SiO_2 spheres (diameter 966 nm) in a solution of 60% H_2O and 40% 2-propanol. This suspension was spin coated onto the TOPCon surface by ramping up to 2000 rpm within 10 s and then switching to the final spin speed of 3250 rpm for 40 s. By this procedure, dense, hexagonally ordered monolayers (as seen in Fig. 2) can be formed. After spin coating the voids in between the spheres were filled by an atmospheric pressure chemical vapor deposition (APCVD) of polysilicon as the matrix material (see Fig. 2). The deposition took place at approximately 850 °C. The deposited silicon can be doped by adding PH_3 to the gas flow. The individual sample types are described as follows:

For optical samples the rear side was passivated with TOPCon and the two sphere grating fabrication steps were conducted on top of the TOPCon surface. As matrix material we deposited undoped silicon with a thickness such that the spheres are just covered by silicon. A fraction of the optical samples has been textured at the front side with random pyramids by a KOH-based solution. All optical samples featured no additional antireflection coating. The optical samples have been characterized using a spectrophotometer with an integrating sphere (Varian Cary 5000).

For the lifetime samples we fabricated symmetric structures with TOPCon layers on both sides followed by the spin coating of spheres and subsequent matrix deposition. Finally the samples received a 30 min annealing step at 450 °C in a hydrogen atmosphere. For the measurement of the life time and the implied V_{OC}, quasi-steady-state photoconductance (QSSPC) was used [28].

For the solar cells, 7 individual cells with an active area of 2×2 cm^2 were processed per wafer. An implanted boron doped p-type emitter with a sheet resistance of 150 Ω/sq and a boron doped diffused selective emitter with 9 Ω/sq underneath the metal contacts were fabricated. The emitter has been passivated with ALD-deposited Al_2O_3, and a double layer antireflection coating consisting of PECVD-deposited SiN_x and evaporated MgF_2 was applied. The front side grid was defined via photolithography and seed layers consisting of a stack of Ti, Pd, and Ag were evaporated. By light induced plating the grid lines were thickened. For the rear side, processes as described above have been used: passivation with TOPCon, sphere deposition by spin coating and matrix deposition by APCVD. The matrix was doped with phosphorus to a level of approximately 1×10^{19} cm^{-3}. The deposited matrix had a thickness of 5 µm and was etched back with a planarizing wet-chemical process. For further planarization and contact formation a 150 nm thick ITO layer was sputter deposited followed by thermal evaporation of silver. The solar cell structure is sketched in Fig. 1.