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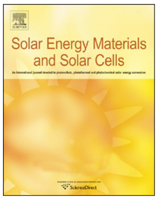

Efficiency increase of crystalline silicon solar cells with nanoimprinted rear side gratings for enhanced light trapping

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ABSTRACT

We demonstrate diffractive rear side gratings to enhance the near infrared light trapping and thus the quantum efficiency of wafer based crystalline silicon solar cells. Binary crossed gratings with a period of 1 μm, produced via nanoimprint lithography and plasma etching, are electrically decoupled from the solar cell by a thin dielectric passivation layer, creating an electrically flat, but optically rough rear side. We fabricated solar cells with thicknesses of 250, 150 and 100 μm and demonstrate a short circuit current density gain due to the grating of 1.2, 1.6 and 1.8 mA/cm^2 for solar cells with planar front surface. For solar cells with pyramidally textured front surface the grating also leads to a small current density gain in the near infrared of approximately 0.3 mA/cm^2 according to EQE measurements, leading to the best cell's efficiency of 21.1%. By optical simulations we show the potential of the grating structure and identify losses in the fabricated solar cells.

1. Introduction

Due to the weak absorption of near infrared light in crystalline silicon, structures that enhance the light path length within the silicon absorber are required, especially when thin substrates are used. Usually, this is done with front side textures like upright random pyramids for monocrystalline silicon [1] or isotextures for multicrystalline silicon [2]. As an alternative to these standard front side textures with feature sizes in the range of several micrometers, light path length enhancing structures at the rear side have been investigated by several groups and show promising optical properties. Goetzberger suggested the use of a Lambertian rear surface in 1981 [3] and Tiedje and Yablonovitch deduced a limit for such Lambertian light trapping [4,5]. Heine and Morf, instead, suggested the use of diffractive structures at the rear side [6,7] and demonstrated possible light path length enhancements up to a factor of five due to gratings. Yu et al. showed, that using nanophotonic structures, the Lambertian limit could be exceeded [8–10]. While numerous works investigated scattering or diffractive light trapping structures for thin film silicon solar cells, both, theoretically (e.g. [11–16]) and at final device level (e.g. [17–21]), many works on diffractive rear side structures for wafer based crystalline silicon solar cells focused on theoretical investigations and optical measurements only (e.g. [22–29]). Peters et al. predicted a photocurrent density gain of up to 1.8 mA/cm^2 for a linear grating optimized with respect to period and depth and 40 μm thick substrates based on wave-optical simulations [22]. Hauser et al. developed a process chain for binary linear and crossed gratings via nanoimprint lithography (NIL) and subsequent plasma etching [30], on which also the processing of the gratings in this work is based. They also showed experimentally that two-dimensional gratings lead to a higher photocurrent gain than one-dimensional gratings, which is in agreement with results from Mellor et al. [24,25]. For the introduction of these light trapping concepts into wafer based silicon solar cells, two aspects are particularly critical: firstly, the increased rear surface area of the structure and possible plasma induced damages can cause low minority carrier lifetimes [31], secondly, the presence of a structured rear side metallization as consequence of the diffractive structure would lead to parasitic absorption [22,25,32]. Hence, a planarization of the structure with a low refractive index material is usually necessary, which increases the number of process steps and complicates the contact formation process [30,33]. Recently, two successful integrations of diffractive rear side structures (sphere gratings and binary, nanoimprinted gratings like in this work) into thick wafer based silicon solar cells have been reported [34,35]. In both works, short circuit current density gains between 1 and 1.5 mA/cm^2 have been achieved for solar cells with a planar front surface and a thickness of 200 and

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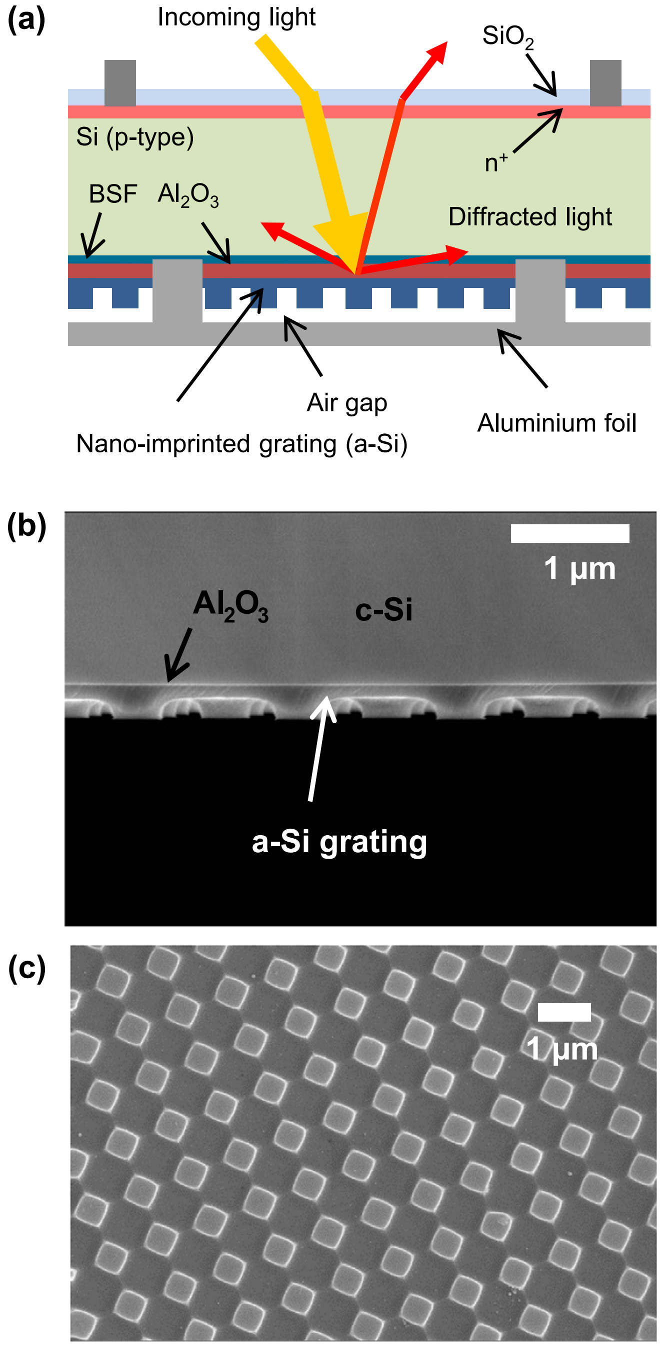

Fig. 1. (a): Schematic structure of the realized solar cell concept: a p-type Si solar cell with passivated emitter at the front, featuring a binary crossed grating at the rear side for enhanced light trapping of near infrared light. For local contacts an aluminium foil was applied. The front side was either planar (like depicted here) or pyramidally textured. (b): SEM-micrograph of the cross section of the grating at the rear side without metallization. (c): SEM –micrograph of the top view showing the crossed grating.

250 μm, respectively. In this work, we demonstrate silicon solar cells with an optically active layer at the rear side as in [35], electrically decoupled from the silicon bulk by a thin, planar passivation layer. The structure, schematically shown in Fig. 1, consists of a binary diffraction grating, which was fabricated via nanoimprint lithography and plasma etching into an amorphous silicon layer. In case of a planar front surface, this leads to a device that is “electrically planar, but optically structured” (EPOS). In terms of reaching highest voltages while also reaching high current densities, this concept might be promising to reach ultimate efficiencies in the long term. In contrast to the sphere grating concept presented in [34], which follows a “bottom-up” approach for the structure fabrication, the concept presented in this paper is a “top-down” approach that requires a mastering but enables the realization of a large variety of structures including additional features, for example for contact formation as presented in [36]. In addition to the results published in [35], we also combine this diffractive rear side structure with a pyramidal front texture (Section 3.2) and investigate the effect of the grating also for thinner wafer based solar cells (150 and 100 μm cell thickness, Section 3.1), where the light trapping effect is more pronounced and where the optimum thickness for ultimately efficient silicon solar cells lies [37]. The rear side metallization has been realized via a laser based foil process (Foil-LFC) [38] that does not require any planarization step due to an optically beneficial air gap between the grating structure and the aluminium foil. Additionally, the Foil-LFC allows for a refractive index contrast between the a-Si grating and air that is higher than in the case of sphere gratings [34] and thus enables very high diffraction efficiencies. In addition to the JV-characteristics, we investigated the wavelength dependent behavior of the cells via external quantum efficiency and reflectance measurements in order to reveal the light trapping effects due to the diffractive rear side grating. Optical simulations based on the simulation framework OPTOS [39,40] were conducted to further understand the effect of the rear side grating (Section 3.3).

2. Experimental methods

The fabricated solar cells feature a PERT (passivated emitter and rear totally diffused) cell structure. As base material, 4 in. float zone p-type silicon wafers with a resistivity of 1 Ω cm and a thickness between 100 and 250 μm were used. On each of the 24 wafers in the batch, seven cells with an active area of 2×2 cm^2 were fabricated. A 120 Ω/sq front side emitter was realized by phosphorous diffusion and a 100 Ω/sq. back surface field by boron diffusion. A 105 nm thick SiO_2 electrical passivation layer was grown on the front side. Despite its very low refractive index, this SiO_2 layer also serves as antireflection coating (ARC). The focus of this work is near infrared light trapping and hence the non-optimum front side ARC is of minor importance. Photolithography, metal evaporation and light induced plating were used to form the front side metal grid. On the rear side, a 10 nm thin Al_2O_3 layer electrically passivates the Si bulk and separates the optical and electrical properties of the rear side. Behind this passivation layer, a sputtered amorphous Si layer is structured by nanoimprint lithography and subsequent plasma-etching. The photoresist is applied via spin coating and patterned using the smart-Nil technology by EVG with a soft PDMS stamp [36]. The reactive ion etching process for the pattern transfer to the amorphous silicon is conducted at an Oxford Plasmalab 133 with SF_6 and O_2 as etching gases [30,35]. It was found that the NIL process did not lead to problems concerning wafer breakage. In [36] it is shown that this even holds for wafers as thin as 50 μm. The reference cells featured no amorphous silicon layer but a 100 nm thick SiO_2 layer instead. The resulting pattern for the grating cells is a binary crossed grating with a period of 1 μm and a material related fill factor of 0.57. A SEM micrograph of the cross section of the grating is shown in Fig. 1(b) and a top-view in Fig. 1(c). For contact formation, foil-based laser fired contacts have been realized [38]. The contact diameter of approximately 40 μm and the 700 μm pitch of the LFC process lead to a contact area of only 0.3%.

For each surface texture combination (planar and textured front, planar and grating rear) calibrated JV and EQE measurements have been conducted by Fraunhofer ISE CalLab for one