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Combining randomly textured surfaces and one-dimensional photonic crystals as efficient light-trapping structures in hydrogenated amorphous silicon solar cells

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ABSTRACT

One of the foremost challenges in achieving high-efficiency thin-film silicon solar cells is in devising an efficient light trapping system because of the short optical path length imposed by the inherent thin absorption layers. In this paper, an efficient light trapping system is proposed using a combination of randomly textured surfaces and a one-dimensional photonic crystal (randomly textured photonic crystal; RTPC). The influence of the texture on the optical performance of RTPCs is discussed using the results of an experiment and a finite-difference time-domain simulation. This RTPC back reflector (BR) can provide high reflectivity and strong light scattering, resulting in an increased photocurrent density of the hydrogenated amorphous silicon (a-Si:H) solar cell. As a result, the highly textured RTPC BR yielded an efficiency of 9.6% for a-Si:H solar cell, which is much higher than the efficiency of 7.6% on flat AZO/Ag BR and 9.0% on textured AZO/Ag BR. This RTPC BR provides a new approach for creating high-efficiency, low-cost thin-film silicon solar cells.

1. Introduction

Light trapping is well established as a technique for improving the energy conversion efficiency in thin-film silicon solar cells [1–4]. In thin-film silicon solar cells with a substrate configuration (*n*–*i*–*p* structure; *n*-doped layer/intrinsic layer/*p*-doped layer), the typical thickness of the indium tin oxide (ITO) front contact ranges from 60 nm to 80 nm for a suitable anti-reflective quality [5–7]. It is difficult to produce a textured surface for additional light trapping effect with such a thin ITO layer. Therefore, in *n*–*i*–*p* thin-film silicon solar cells, light trapping is primarily caused by the textured back reflector (BR), which plays a more crucial role than in their superstrate (*p*–*i*–*n*) counterparts [6,8]. The most widely used BRs for high efficiency *n*–*i*–*p* thin-film silicon solar cells are composed of aluminum-doped zinc oxide (AZO)/Ag with a randomly textured surface, which can be produced by combining the BR structure with a thermally roughened textured Ag [8,9] or a silver-covered randomly textured substrate [10–12]. It is well known that a larger-scale texture provides superior light trapping [10,13]. However, in traditional BRs, there is a trade-off between a suitable light scattering texture and the losses due to surface plasmon absorptions from the rough surface of the metallic layer [14–16]. Such losses are cumulative over each reflection on the active layer/rough metallic interface and become severe at higher photon wavelengths because multiple optical passes are required [17]. In addition, the cost reduction achieved through efficiency enhancement using AZO/Ag BRs is partly counterweighed by the expensive raw material, silver.

In the past decade, several advanced light trapping concepts and structures, such as the three-dimensional photonic crystal intermediate reflector [18], modulated surface textures [19], plasmonic light trapping [20,21], periodic honeycomb pattern substrates [22], and photonic design [23,24], have attracted much interest for improving the performance of solar cells. A highly promising alternative approach is to use a dielectric one-dimensional photonic crystal (1D PC), which is a multilayer structure in which two layers (bilayers) with a high refractive-index contrast are periodically stacked [25,26]. The 1D PC has a wide forbidden band with a range of several hundreds of nanometers with nearly 100% reflectivity, which guarantees that almost no light can transmit through the backside [27–29]. So it can be used as a

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spectrally selective intermediate reflector (with high conductivity) in the tandem solar cells [30] or a broad spectrum BR (dielectric) in the thin-film silicon solar cells [26,27,31,32]. The conventional 1D PC BR has been treated as a distributed Bragg reflector (DBR), in which the thickness of the individual layers was calculated on a quarter-wavelength basis for the Bragg wavelength λ_0 [26,27,31,32]. However, many groups of layer thickness contrasts (with identified materials and layer sequence thicknesses) can be used to enable the photonic bandgap (PBG) of the 1D PC to fully cover the light trapping range needed for thin-film silicon solar cells with the DBR structure [33]. In addition, light will couple to the top three layer sequences of the 1D PC and can be absorbed if one of the bilayers is absorptive [33]. In this case, a good method to improve the performance of the 1D PC is to decrease the thickness contrast of the absorptive layer with respect to the non-absorptive layer while retaining the PBG area that covers the light trapping range [33]. The combination of a transparent conductive oxide (TCO) layer and 1D PC can simultaneously serve as the back electrical contact and BR in a thin-film silicon solar cell while avoiding intrinsic losses due to the surface plasmon modes originating from the rough surface of the metallic layer [32–34].

Besides high reflectivity, a highly efficient BR must promote strong scattering of incident light back into the absorber to increase the effective optical path length in the functional cell. In order to induce scattering in a 1D PC with a TCO layer, some groups have suggested adopting two-dimensional gratings on the TCO layer [35] or even on the 1D PC [36]. Although simulation results for these composites show a significant improvement in optical absorption, no experimental results have been reported. In fact, the steep valleys of the gratings would inevitably induce unwanted defects within the active layer and deteriorate the device performance [1,37]. This issue can be prevented using methods such as post-chemical AZO etching, which can moderately randomize the texture of the TCO layer surface [34]. In this method, a relatively thick AZO layer is needed, which could lead to additional parasitic absorption [34]. This is problematic in solar cells with a broad absorption wavelength range, such as single-junction microcrystalline silicon solar cells (μc-Si:H) [38] or a-Si:H/μc-Si:H tandem solar cells (in which the absorption wavelength can extend to 1100 nm) [39], because the free-carrier absorption of the AZO layer increases with increasing wavelength in the IR region [3,40]. L. Zeng proposed a novel textured PC by depositing a 1D PC directly on a rough surface (periodic grating) and experimentally demonstrated its improved efficiency in an ultra-thin crystalline silicon solar cell by using a complicated integrated circuit design [26,27]. This method is easily applied in *n*–*i*–*p* thin-film silicon solar cells owing to the layer-by-layer deposition process. The substrate roughness should translate to the post deposition layers to induce scattering, and a thinner TCO layer can be adopted to reduce parasitic absorption. O. Isabella fabricated an *n*–*i*–*p* thin-film silicon solar cell with a dielectric DBR on a textured Asahi-U-type TCO substrate [32] and obtained an enhanced external quantum efficiency (EQE) in the long wavelength range.

Light propagation within the bulk of the PC was previously assumed to be forbidden, which led to the assumption that 100% frequency reflection occurred within the PBG because the light incident on the PC surface must be reflected [25,28]. Therefore, focus has been kept directly on device performance in the works with textured (periodic or random) 1D PC [26,27,32]. However, the influence of the texture on the optical performance of 1D PCs remains unclear, which prevents the determination of optimized PC configurations and limits the potential of 1D PCs in thin-film silicon solar cells. The conventional solution might suggest adopting as many layer sequences as possible to guarantee reflectivity, although the efficacy of this method is unclear. Moreover, in actual solar cell production, it is preferable to use fewer layer sequences in order to reduce fabrication time and material cost.

In this study, we developed a randomly textured photonic crystal (RTPC) BR to enhance the performance of *n*–*i*–*p* a-Si:H solar cells by depositing a 1D PC onto a randomly textured AZO template. We firstly studied the influence of the textured surface on the total reflectance, transmittance, and haze factor of the RTPC BRs. Then, we used commercial finite-difference time-domain (FDTD) software to study the optical characteristics of a flat 1D PC with angled incidence, which can help explain the optical losses of the RTPC. Finally, the influence of the texture on the performance of RTPC-based solar cells was examined. Although we focused on *n*–*i*–*p* a-Si:H single-junction solar cells with RTPC BRs, our analytic techniques can be applied to multi-junction devices or *p*–*i*–*n* devices as well.

2. Experimental and simulation methods

Fig. 1 shows a schematic diagram of an *n*–*i*–*p* a-Si:H solar cell with an RTPC BR. A thick AZO film (1.5 μm) was firstly deposited on a flat glass using a radio-frequency (RF) magnetron sputtering system with a sintered ceramic ZnO target having 2 wt% Al_2O_3. The AZO film was then chemically etched in 0.5% HCl to create a crater-like textured surface. Subsequently, 1D PC layers were deposited on the rough surface to form the RTPC. It is not easy to obtain two materials with a high refractive-index contrast that do not absorb visible light. Here, we used a-Si:H ($n\cong4$ at $\lambda=650$ nm) and SiO_x ($n\cong1.5$ at $\lambda=650$ nm) as the higher- and lower-refractive-index materials, respectively, to form the 1D PC because they not only are compatible with the thin-film silicon solar cell deposition process but also provide a sufficiently high index contrast. The 1D PC or RTPC structure is alternatively stacked with 155-nm-thick SiO_x as the top layer and 25-nm-thick a-Si:H as the bottom layer. The a-Si:H and SiO_x layers were deposited in the same chamber using a multi-chamber RF plasma-enhanced chemical vapor deposition (PECVD) system. The gas sources for the deposition of the SiO_x layer were CO_2, SiH_4, and H_2. In order to achieve a non-absorptive SiO_x layer in the visible–near-infrared (NIR) region, a high $[CO_2]/[SiH_4]$ concentration ratio of 10 was used. Note that the bulk absorption of RTPC still occurs because of the absorptive a-Si:H layer. Here, we used a thinner a-Si:H layer (25 nm) to reduce the bulk absorption while maintaining the coverage of the PBG in the light trapping range. We deposit SiO_x on top of the a-Si:H because total internal reflection occurs more readily at the AZO/SiO_x

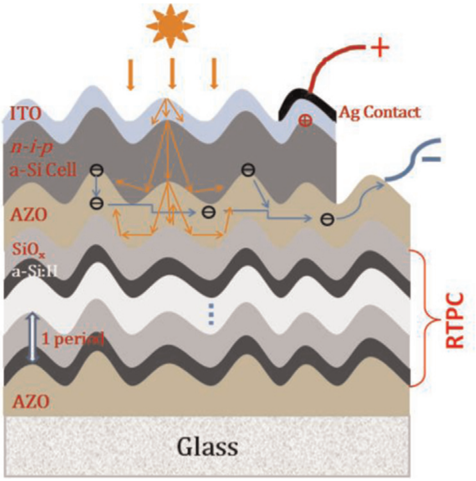

Fig. 1. Schematic diagram of an RTPC-based *n*–*i*–*p* a-Si:H solar cell.