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Photonic crystal structures for light trapping in thin-film Si solar cells: Modeling, process and optimizations

Xing Sheng*, Lirong Z. Broderick, Lionel C. Kimerling

Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

In this paper, we present our efforts on studying light trapping in thin-film silicon solar cells using photonic crystal (PC) based structures. Specifically, we propose a photonic backside texture combining periodic gratings and a distributed Bragg reflector (DBR). The mechanisms of this integrated photonic design are theoretically studied and compared with conventional PCs. We experimentally fabricate the texture using lithographic and self-assembled method on thin-film single crystalline Si (c-Si) and microcrystalline Si (μc-Si) cells. We analyze the effects of the photonic textures on different cells and demonstrate the performance improvements. A numerical method is developed to explore the optimal multiscale textured surface and investigate light trapping limits in the wave optics regime. Using a detailed balance analysis, we show that it is possible to reach over 20% efficiency for 1.5 μm Si cells through optimal device design and fabrication.

1. Introduction

Photovoltaic (PV) technology is considered to be a promising technique for solar energy utilization and has already achieved wide applications for space and terrestrial power generation [1]. Among all the semiconductor solar cells, silicon (Si) based solar cells have dominated most of the PV market due to the abundance and mature technology of Si. Further cost reduction requires less material usage and a thin-film Si based platform [2,3]. The efficiency of thin-film Si solar cells critically depends on optical absorption in the Si layer since single-crystalline (c-Si), amorphous (a-Si), and microcrystalline silicon (μc-Si) have low absorption coefficients in the red and near-infrared wavelength ranges. Nowadays, thin-film Si solar cells still show inferior performances compared to their bulk c-Si based counterpart. Therefore, an effective light trapping design is indispensable to achieve high efficiency modules. Traditional light trapping schemes such as textured transparent conductive oxides (TCOs) and metal reflectors [4] lack the ability to precisely control and optimize the textured surface in experiments and numerical models. Recently, one-, two- and three-dimensional photonic crystals (1D, 2D and 3D PCs) have also been proposed to enhance the light trapping [5–8]. Such PC structures can be optimized numerically but still remain challenging for low-cost fabrication, especially for 2D and 3D PCs. In addition, some fundamental questions have not yet been solved for light trapping and efficiency limits in thin-film Si solar cells.

This report aims to address the above questions by summarizing our recent progress on designing and fabricating light trapping structures in thin-film Si cells. We begin by introducing a light trapping design combining periodic gratings and DBR. We then review the experimentally realized devices and systematically discuss the device performances. Finally, we develop numerical models to explore the optimized photonic texture and examine the fundamental limits for light trapping and efficiency limits in thin-film Si cells.

2. Theory

Fig. 1 illustrates thin-film Si cells with different photonic crystal based back reflectors, as well as the wave propagations. Those simulation cells have periodic boundary conditions in the lateral direction, under normally incident TE polarized light (the electric field perpendicular to the incident plane) at 800 nm. The active device layer is 1.5 μm c-Si. The electric field distributions are simulated with the finite-difference time-domain (FDTD) method [9,10]. In Fig. 1(a), 5 pairs of alternating a-Si ($n_{a\text{-}Si}=3.6$, $d_{a\text{-}Si}=56$ nm) and SiO_2 ($n_{SiO2}=1.45$, $d_{SiO2}=138$ nm) layers form a distributed Bragg reflector (DBR, or 1D PC). This designed DBR

* Corresponding author. Current address: Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. Tel.: +1 412 992 6749.
E-mail address: shengxingstars@gmail.com (X. Sheng).

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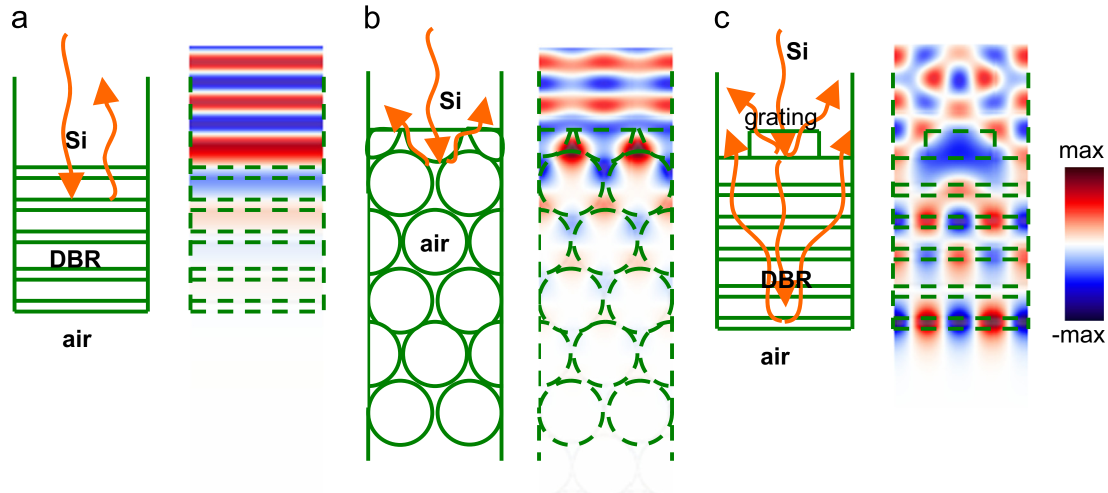

Fig. 1. Simulated electric field distribution in thin-film c-Si cells with different light trapping schemes: (a) with a DBR, made by 5 pairs of a-Si (56 nm) and SiO_2 (138 nm); (b) with a 2D PC, made by air holes embedded in Si (lattice period 350 nm, hole radius 168 nm); and (c) with grating (period 800 nm and thickness 100 nm) and DBR [12].

exhibits a complete photonic bandgap for both TE and TM polarized light approximately from 650 nm to 1000 nm [11,12]. When light is incident on such a DBR from the thin-film c-Si, it is totally reflected. The second design illustrated in Fig. 1(b) consists of a 2D photonic crystal in the back, made of a triangular lattice of cylindrical air holes embedded in Si (lattice period $a=350$ nm, hole radius $r=0.48$, $a=168$ nm). Such an optimized 2D photonic crystal structure can provide a complete bandgap for both TE and TM light [13], in the range between 673 nm and 814 nm. Furthermore, the light incident on the 2D PC ($\lambda=800$ nm) is not only totally reflected, but also diffracted because of the periodicity introduced in the lateral direction, further increasing the light path length. Therefore, 2D PC structures can provide better light trapping performance than a 1D DBR at specific wavelengths. However, thin-film Si cells need a reflecting and scattering component that can work in a broad band covering the entire red and near-infrared spectral range. Compared to the DBR, the optimized 2D PC only has a very narrow bandgap [13] and cannot provide desired light trapping for broad band applications. Furthermore, experimentally fabricating such a structure has lots of technical challenges and is not feasible for low cost and large area PV applications. In order to combine the benefits from both 1D and 2D PC structures, we propose an integrated PC structure illustrated in Fig. 1(c), including the DBR in Fig. 1(a) as well as a periodic grating [14,15]. Specifically, the grating is assumed to be made of Si and SiO_2, with a period of 800 nm, a duty cycle of 0.5 and a thickness of 100 nm. The operational principles of such an integrated PC structure are explained in Fig. 1(c). When the grating layer is embedded between the Si and DBR, scattering is introduced. The light is not only scattered backward but also forward into the DBR, due to the band folding introduced by the periodic grating [12]. However, no field can penetrate into the bottom air layer, and almost all the waves are totally reflected back at the DBR/air interface and eventually get trapped in the thin-film device. Therefore, the texture PC structure in Fig. 3(c) combines the benefits of the wide reflection gap of the DBR and the strong scattering of the grating, leading to effective broad band light trapping. In addition, this structure can be more easily fabricated compared to the complicated 2D PCs, with a potential for low-cost productions. The DBR structure also shows superior performance compared to conventional metal reflectors, because of the high reflectivity (nearly 100% for DBR vs. about 80–90% for metals) in the desired spectral range [12].

3. Experiment

3.1. Thin-film c-Si cells with lithographically defined gratings

Our proposed grating and DBR structures integrated with 5 μm thick c-Si solar cells [16] are shown in Fig. 2(a). To fabricate such a device, silicon-on-insulator (SOI) wafers are used as the starting materials. Processing of the SOI active layer includes grating formation with interference lithography, followed by reactive ion etching, DBR deposition using plasma enhanced chemical vapor deposition (PECVD), bonding the active layer to a new handle wafer, removal of the original handle wafer, forming an antireflective coating (ARC) on the newly exposed Si surface, lateral p-i-n junction creation by ion implantation, and metallization with interdigitated contacts for both p-doped and n-doped regions on the top surface. The cross-sectional TEM image of the fabricated PC structure is shown in Fig. 2(b). The structural parameters of the PC structures are determined by numerical simulations and optimizations [6,15]. The cells without any reflectors and only with a DBR are also fabricated for comparison.

Current–voltage (J–V) measurements in Fig. 2(c) demonstrate that each back structure improves absorption and cell efficiency, with the cell combining grating and DBR achieved the highest short-circuit current J_{sc} of 17.5 mA/cm^2, compared to 14.7 mA/cm^2 for the reference cell. The measured power conversion efficiency is increased from 7.68% for the reference cell to 8.82% for the cell with grating and DBR. A relative efficiency enhancement of 14.8% is obtained. The measured EQE spectra shown in Fig. 2(d) also reveal that the combined grating and DBR structure obtains the highest absorption enhancement in the spectral range from 600 nm to 1000 nm.

3.2. Thin-film micro-crystalline Si cells with self-assembled gratings

The thin-film c-Si solar cells made from SOI wafers demonstrate relatively high efficiencies; however, the process and starting materials are not economically viable for scale-up production. In addition, the periodic grating in Fig. 2(b) is lithographically defined, which further increases the production cost. In Fig. 3 we apply our design on low-cost μc-Si solar cells, introducing a self-assembled process to fabricate the similar light trapping structures [11]. The μc-Si solar cell structure is shown in Fig. 3(a). The active device layer is a 1.5 μm thick μc-Si p-i-n junction, produced by a