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Integration of Self-Assembled Porous Alumina and Distributed Bragg Reflector for Light Trapping in Si Photovoltaic Devices

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Abstract—Light trapping is an important issue for thin film silicon photovoltaic cells due to the limited absorption coefficient for near infrared light. In this letter, we present a photonic structure that combines porous anodic aluminum oxide with a distributed Bragg reflector (DBR) on the backside of Si cells for light trapping. Simulation results show that this low-cost, self-assembled structure can provide more than 50% relative efficiency enhancement for a 2 μm thin film crystalline Si solar cell, as compared to a reference cell without any back structure. As a proof of concept, we incorporated the backside structure into thick silicon wafers. The enhancement of light absorption near the band edge of silicon is demonstrated for our proposed light-trapping structure, in agreement with the theoretical predictions.

Index Terms—Distributed Bragg reflector (DBR), grating, light trapping, photovoltaics, self-assembly.

I. INTRODUCTION

CURRENTLY, most commercial photovoltaic cells are based on silicon wafers. Cost reduction of silicon wafer-based solar cells is challenging because it is dominated by the cost of the starting material. Alternatively, thin film silicon solar cells based on inexpensive substrates are designed to reduce silicon consumption by 100 fold so that material cost becomes negligible. However, as films become thinner, the absorption of photons, especially those with longer wavelengths, is reduced. This problem is severe especially for silicon because of its inefficient indirect bandgap absorption, leading to a decrease in power conversion efficiency. To overcome this limit, several light-trapping schemes were proposed to increase optical absorption in thin film silicon. For example, 1-D photonic crystal was proposed to enhance the absorption in the intrinsic Si layers and potentially surpass the light-trapping limit [1]. Recently, a textured photonic crystal (TPC) back reflector was designed, which combines a 1-D reflection grating and a distributed Bragg reflector (DBR) [2], [3]. The DBR forms a 1-D photonic crystal with nearly 100% reflectivity in the near-infrared range to prevent light leakage through the backside, while the grating diffracts the incident light into oblique angles to significantly increase the optical path length. By integrating the TPC structure into 5-μm thick monocrystalline silicon solar cells, a significant enhancement of the external quantum efficiency (EQE) was observed in a wavelength range from 600 to 1000 nm, leading to a 19% increase in the cell efficiency [4]. However, this method has its own limitation. Since photolithography and other cleanroom facilities are required to fabricate the subwavelength gratings [5], the TPC structure cannot be scaled to large area process. To achieve scalability to large area solar cells without lithography, we have proposed a self-assembled 2-D anodic aluminum oxide (AAO) grating and preliminarily studied its performance [6]. However, for simplicity, the modeling did not incorporate the actual AAO structure so it lacks direct correlation to the experimental results. In this letter, we present a detailed quantitative analysis on the periodicity of the fabricated AAO structure and simulate the corresponding light-trapping performance. The effect of deviation from perfect periodic structure is also analyzed. The agreement between the simulation and experimental results establishes a guide to design self-assembled 2-D AAO gratings for light trapping.

II. APPROACH

To fabricate the 2-D AAO grating via self-asembly, a 150-nm-thick aluminum film is deposited on a silicon substrate. Then the Al film is anodized in a 4 wt% phosphoric acid at a voltage of 150 V until the aluminum film is completely oxidized to aluminum oxide. During anodization, the temperature is maintained at 5 °C to prevent electrical breakdown. Afterwards, the samples are immersed in 5 wt% phosphoric acid for about 2 hours at room temperature to widen the pore size and remove the barrier layer. Subsequently, five pairs of alternating amorphous Si (65 nm) and SiO$_2$ (170 nm) layers are deposited by plasma enhanced chemical vapor deposition (PECVD) to fill the pores and form a photonic bandgap and achieve 99.9% reflectivity in the red and near infrared range.

The inset of Fig. 1 shows a scanning electron microscope (SEM) image of the porous alumina structure after the pore widening treatment. The regularity of the pore distribution is revealed by 2-D fast Fourier transformation (FFT) of the SEM image, which is similar to the diffraction pattern of a
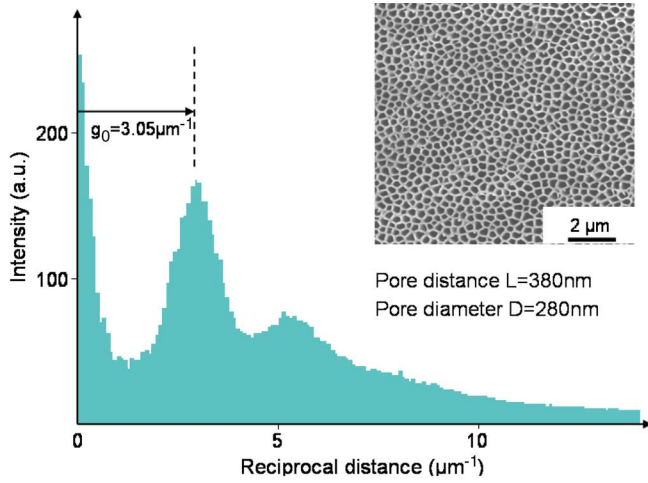
Fig. 1. FFT intensity profile of SEM image as function of reciprocal distance from origin, from which interpore distance of AAO is derived. Inset shows SEM image of AAO after pore widening. Averaged pore distance L and pore diameter D are also shown.

Fig. 2. Simulated absorption spectra for 2-μm-thick silicon with different backside structures. (a) Schematic cell structure with grating and DBR in back. Grating is composed of silicon rods embedded in alumina matrix. Topview: (b) perfectly periodic hexagonal grating (PG) and (c) real AAO grating with disorder. FDTD calculation domains are also shown by dashed boxes. Periodic boundary condition is used for supercell approach. Parameters L and D are given in Fig. 1.

polycrystalline material. To derive the characteristic length scale of AAO, the averaged radial intensity distribution is plotted as a function of distance from the center (Fig. 1) [7]. From the scattering peak at the characteristic spatial frequency of $g_0 = 3.05$ μm^{-1}, the average pore-to-pore distance of the near-hexagonal AAO can be determined to be $L = 2/\sqrt{3}g_0$, which is about 380 nm [8]. This calculation result agrees with [9] which showed the interpore distance of AAO is linearly proportional to the applied anodization voltage: $L = 2.5$ V $= 2.5 * 150 = 375$ nm. Furthermore, the average pore diameter of AAO is determined from the SEM image to be about 280 nm.

III. NUMERICAL SIMULATION

To predict the light-trapping effect of the fabricated AAO and DBR backside structure quantitatively, numerical simulations based on finite difference time domain (FDTD) were performed for 2-μm-thick silicon. In the model [Fig. 2(a)], the DBR consists of five pairs of amorphous Si (65 nm) and SiO$_2$ (170 nm) layers, while the 150-nm-thick grating is formed by Si cylinders embedded in the AAO matrix. Different from our previous work [6], a more accurate structure is used for modeling, which employs a hexagonal instead of a rectangular grating. For simplicity, each layer in the DBR is assumed to be flat. In reality, there may be undulations that do not degrade the DBR performance [4]. As an approximation, a perfectly periodic structure is used in Fig. 2(b) with $L = 380$ nm and $D = 280$ nm. To further approach the real AAO porous structure, a periodic hexagonal pattern with distorted subunit cells, taken from a SEM image [Fig. 2(c)], was also simulated as a comparison to the perfect periodic structure. With the refractive indices of different materials given in [10], we calculate absorption spectra of the silicon layers with different backside structures (see Fig. 2). At wavelengths between 0.5 and 1.1 μm, stronger absorption peaks for silicon with DBR (green color) are caused by thin film Fabry-Perot interference. When the grating layer (either the periodic grating or the real AAO grating) is added, the absorption
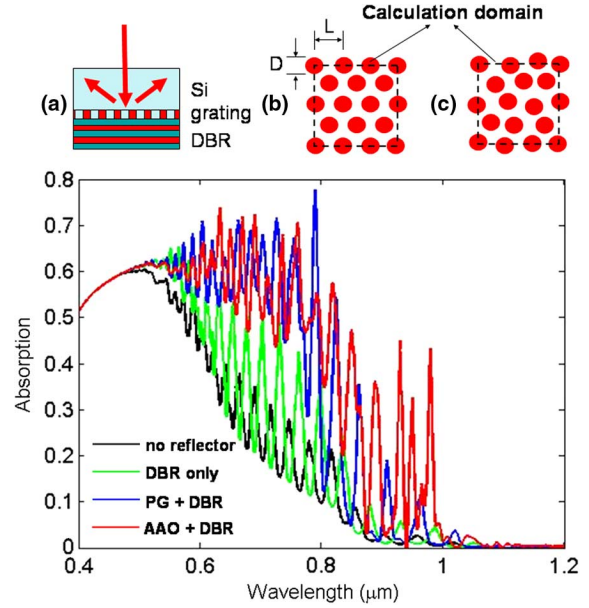
enhancement is even more significant (blue and red color) since the light can be diffracted into oblique angles to enhance the absorption length.

A more accurate and complete model [11] is applied in this work to derive all photovoltaic parameters, including short circuit current J_{sc}, open circuit voltage V_{oc}, and solar cell efficiency η. For the crystalline silicon solar cell, the current density J as a function of the voltage V can be calculated by [11]

$$J = e \int s(\lambda) \cdot A(\lambda) \mathrm{d}\lambda - \frac{2\pi e(n^2 + 1)E_g^2 kT}{h^3 c^2} \exp\left(\frac{eV - E_g}{kT}\right) \tag{1}$$

where n is the refractive index of silicon, and E_g is the silicon bandgap. The total number of absorbed photons can be calculated by integrating over the product of the calculated absorption spectrum $A(\lambda)$ and standard air-mass 1.5 G solar spectrum $S(\lambda)$ to derive the short circuit current. Then the cell efficiency can be calculated from $\eta = J_{\max} V_{\max} / \int s(\lambda) \mathrm{d}\lambda$. As shown in Table I, the DBR gives rise to a 23% relative enhancement of cell efficiency. The combination of periodic grating (PG) and DBR structure indicates a 51% enhancement, while the AAO grating we fabricated is capable of achieving an even higher increase (53%), compared to bare silicon without any reflector on the back surface.

IV. EXPERIMENTAL RESULTS

To demonstrate the light-trapping effect of the AAO and DBR structures as a proof of concept, we implement these photonic structures on the backside of a 300-μm-thick, double-side polished silicon wafer, which does not contain an anti-reflective coating for the processing simplicity. Since photons at short

TABLE I
SIMULATED CHARACTERISTICS OF 2-μm CRYSTALLINE SILICON SOLAR CELLS
WITH DIFFERENT BACKSIDE STRUCTURES

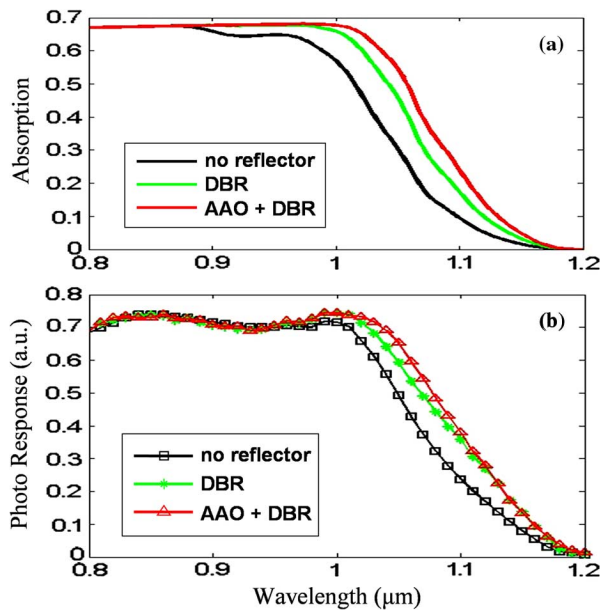| Cell Type	J_{sc} (mA/cm^2)	V_{oc} (V)	Efficiency	Relative Enhancement
No reflector	12.3	0.777	8.2%	-
DBR	15.1	0.782	10.1%	23%
PG+DBR	18.3	0.787	12.4%	51%
AAO+DBR	18.8	0.788	12.5%	53%

Fig. 3. (a) Calculated absorption spectra and (b) measured photoconductive spectral response of 300-μm-thick silicon samples with and without DBR/AAO+DBR on backside of wafers.

wavelengths are completely absorbed by the thick active silicon layer within one pass, to observe the light-trapping effect we focus on wavelengths near the silicon bandgap, around 1.15 μm, where the absorption coefficient is small. The light-trapping effect is evaluated by measuring the spectral dependency of the photoconductivity of a sample with and without light-trapping structures. Under monochromic illumination from 0.8 to 1.2 μm, the photocurrent of the silicon wafers is measured by a lock-in amplifier at a fixed bias (1 V). Photoconductivity ($\Delta\sigma$) in semiconductors is directly related to the excess carrier density (Δn) generated by photon absorption

$$\Delta\sigma = \Delta n \cdot e\mu \qquad (2)$$

where μ is the carrier mobility. Therefore, light-trapping effects can be demonstrated by an enhanced photoconductive response. The calculated absorption and measured photoconductive spectral response for samples with different backside structures are shown in Fig. 3(a) and (b), respectively. The model that is used

here is identical to that employed in the numerical calculations in Fig. 2, except that a much thicker silicon layer is used. As shown in Fig. 3(b), an increase in the photoresponse can be clearly observed above 1.0 μm for a backside DBR structure, while the integration of an AAO and DBR can achieve even higher performance, in agreement with our calculations shown in Fig. 3(a). This result experimentally confirms that AAO and DBR structures can be applied for optical path length enhancement. The electrochemistry approach of self-assembled AAO can be readily scaled to large area solar cells at low cost.

V. CONCLUSION

In conclusion, we propose a novel photonic light-trapping structure, which can be easily fabricated using anodic porous alumina and DBR deposition. Numerical simulations indicate that this combined photonic structure is capable of improving the photovoltaic cell efficiency by more than 50% for thin film crystalline silicon. To demonstrate this effect, photoconductance measurements based on thick silicon wafers are performed to confirm the enhancement of photon collection near the silicon bandedge, in good agreement with the simulation results. Considering a thin-film crystalline silicon cell with a thickness of several microns, the efficiency increase would be much more significant. The self-assembly of AAO can easily be scaled to large area solar cells. These results provide a path to achieve low-cost and strong efficiency enhancement for thin film silicon solar cells.

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