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Enhanced Light Absorption in Ge/Si Quantum Dot Solar Cells by Surface Photonic Nanostructures

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Abstract

We numerically investigate the effect of surface photonic nanostructures on light trapping in Ge/Si quantum dot (QD) solar cells and ultrathin crystalline silicon (c-Si) solar cells. We clarified that light trapping is enhanced on increasing the dip depth of the surface phonic nanostructure. The enhanced light trapping is due to irreversible light transmission at the surface photonic nanostructure, which causes both reduced surface reflection and enhanced internal reflection. In addition, this irreversible light transmission characteristic is robust against conventional antireflection coating. Our findings indicate that this surface nanostructure exhibits a unique functionality that can lead to significant advances in QD solar cells and ultrathin-film solar cells.

1. Introduction

Light management in photovoltaic cells is of great importance because it allows for increased efficiency and reduced cost of materials [1]. In thin crystalline Si (*c*-Si) wafers, the absorption in the near-infrared region of the solar spectrum is significantly reduced because *c*-Si is an indirect bandgap semiconductor. Currently, the surface texture of *c*-Si solar cells has been formed by a wet chemical process utilizing the anisotropic etching rate of c-Si [2,3], and the dimensions of the surface texture and cell thickness are larger than the wavelength of the light. In such textured wafers, the maximum enhancement of the optical path length in a weakly absorbing medium has been theoretically predicted to be $4n^2$ times the single-pass absorption, where n is the refractive index of the absorption material [4].

By reducing the thickness of the absorber material, conventional light trapping which have feature sizes around 10 µm are not suitable. In addition, we need to consider antireflection (AR) coatings to optimize optical absorption. To reach and overcome the $4n^2$ limit, novel concepts for efficient light trapping have been explored, particularly in the sub-wavelength regime [5].

In addition, to overcome the limits of conventional single-junction devices, solar cells using quantum dots (QDs) have been proposed and extensively studied. We have explored the feasibility of *c*-Si based Ge quantum dot solar cells [6–8], and found that enhancement of light absorption in Ge QDs is critical for efficient photon energy conversion [6,8]. To increase light absorption in QDs, light trapping technique that is compatible with Ge/Si QD solar cells is necessary. We recently demonstrated that surface photonic nanostructures fabricated by a wet etching technique from vertically aligned QDs [Fig. 1] causes enhanced photon energy conversion efficiency with respect to reference cells without photonic nanostructures [9]. Our previous works clarified that the surface photonic nanostructure reduces the surface reflection loss [10], and increases the light absorption in the near-infrared region [11]. However, the mechanism of light trapping in the photonic nanostructures and the effect of AR coating are not well understood.

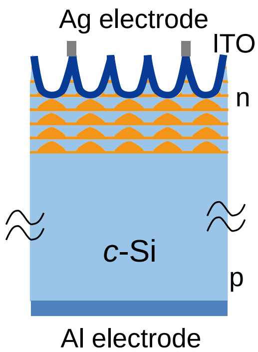

Fig. 1 Schematic illustration of Ge/Si QD solar cells with surface photonic nanostructures.

In this paper, we numerically study the mechanism of light trapping due to the surface photonic nanostructures. Our findings indicate that this surface nanostructure exhibits a unique functionality that can lead to significant advances in QD solar cells and ultrathin-film solar cells.

2. Results and Discussions

To evaluate the light trapping, the electric field density in the absorber is calculated using the finite-difference time-domain (FDTD) method. The light trapping performance is evaluated by the enhancement of electric field density in an absorber. To facilitate our calculation, we used photonic nanostructures of Si with a 400-nm corrugation period on a Si substrate with D ~ 2-μm thickness, as illustrated in Fig. 2(a). The dip depth is changed by tuning the curvature of the holes. The rear side of the Si substrate is covered with a perfect electric conductor (PEC).

Figure 2(b) shows the electric field density for photonic nanostructures with and without AR coating as a function of dip depth for 1000-nm-wavelength light. At zero-depth condition, the AR coating increases the electric field density, which is explained by the reduced surface reflection. With increasing dip depth, the electric-field density gradually increases even in the photonic nanostructure with AR coating. Further increase in dip depth causes the reduced electric-field density, which is due to the reduced light trapping.

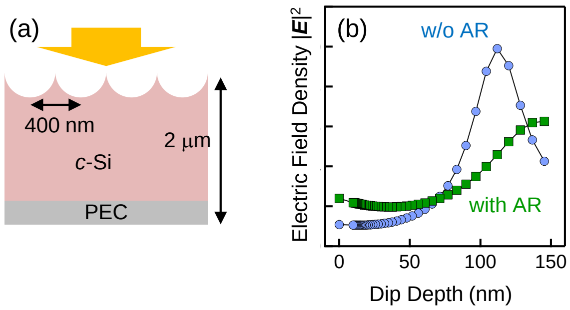

Fig. 2 (a) Schematic of photonic nanostructures used for FDTD simulation. (b) The electric-field density for the photonic nanostructures with (squares) and without (circles) AR coating.

Next, we investigated the optical properties of the surface photonic nanostructures. Figure 1(d) shows the reflectance for 1000-nm-wavelength light at the interface between air to the Si substrate. Reflectance decreased with increasing dip depth in all spectral ranges [10]. To understand the mechanism of reduced reflectance, light transmission in the opposite direction, that is, light transmission from Si to air, is shown in Fig. 3(b). As opposed to light incident from air, the reflectance for light from the Si layer increases with increasing depth. This behavior is not simply explained by a conventional AR coating in which gradual changes of index lead to reduced reflection compared to an abrupt change of index. Reflectance for Si layer covered with a low-refractive-index material (n ≈ 2) with 100-nm thickness reduces to less than 0.1 for both directions. These results indicate that irreversible light transmission occurs because of the surface photonic nanostructures. Such irreversible transmission causes enhanced light trapping, in which, due to coupling to higher order diffraction modes at the surface photonic nanostructures, the incident light into the surface photonic nanostructures would be scattered more efficiently to the Si substrate. Enhanced irreversible transmission at the photonic nanostructures is quite different from conventional light trapping based on Lambertian light scattering and conventional AR coating and would be a unique functionality that can lead to significant advances in light trapping for QD solar cells and ultrathin-film solar cells.

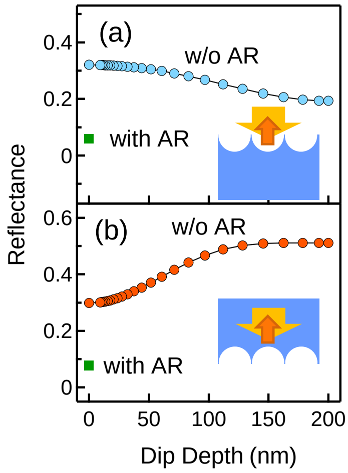

Fig. 3 (a) Reflectance at the air–Si and (b) the Si–air interfaces as a function of dip depth.

3. Conclusions

We numerically investigated the mechanism of light trapping in surface photonic nanostructures. From optical characteristics such as scattering, reflection, and transmission at the surface photonics nanostructures, we found that the enhanced light trapping originates from irreversible light transmission at the surface photonics nanostructures. This behavior of the surface photonic nanostructures is quite different from what is expected of conventional AR coating layers. The enhanced light trapping demonstrated in this study would contribute to significant advances in ultrathin-film solar cells.

Acknowledgements

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