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Optical characterization of double-side textures using photonic nanostructures for thin-wafer c-Si solar cells

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Abstract

As efficient light management in thin-wafer crystalline silicon (c-Si) solar cells, the double-side textures have attracted attention. Here, we perform the application of photonic nanostructure fabricated using quantum dot arrays to front-side texture of the double-side textures. We found that the surface photonic nanostructure exhibits reduced reflectance (<0.1) and the bottom textures results in enhanced light absorption due to light trapping. In addition, we evaluate the light absorption using photoluminescence measurement, indicating that a part of enhanced optical absorption may be caused by parasitic absorption.

1. Introduction

Light management in crystalline silicon (c-Si) Si solar cells is a topic of great interest. This is because the use of thinner Si wafers is important to reduce the production cost in c-Si solar cells but efficient light trapping of near-infrared light is required to absorb incident photons sufficiently. As a promising approach, double-side textured structures with a periodic nanograting on the front-side (FS) for antireflection and with a pyramidal texturing on the back-side (BS) for light scattering have been proposed [1]. This approach has been demonstrated using FS black silicon [2].

To obtain further enhanced light trapping, a use of surface photonic nanostructures is a possible approach. Photonic nanostructures at the submicron scale such photonic crystals, in which new electromagnetic wave phenomena may attribute to efficient light management, have attracted attention for both enhanced light trapping and reduced surface reflection loss [3]. We have previously demonstrated a technique to form photonic nanostructures by using a simple maskless wet etching of Ge dot multilayers on c-Si solar cells [4-7]. This technique forms a submicron nanostructure larger than the black silicon but smaller than that of random pyramidal texture. The height and shape of this photonic nanostructure can be systematically controlled by optimizing the conditions of Ge dot multilayer growth and wet etching.

In this paper, we report the optical properties of double-side textured silicon wafers using the front-side photonic nanostructures. We found that the low surface reflection is obtained in the surface photonic nanostructures and that optical absorption in the near-infrared region increases in double-side textured Si wafer.

2. Experimental

The double-side textured Si wafer [Fig. 1(a)] were fabricated as follows. The SiN_x protective films were deposited on one surface of p-type Si (100) substrates with a thickness of 380 μm. The samples were chemically etched in an alkali-based solution to form the microtexture on one surface. Then, the SiN_x protective films were removed with a H_3PO_4 solution. Next, SiO_2 films were formed on the textured surfaces as protective layers. After cleaning with a mixture of sulfuric acid and hydrogen peroxide and a subsequent HF dip, the samples were loaded in the chamber of a gas-source molecular beam epitaxy system. The SiO_2 protective films on the phosphorous-doped layer were removed in the HF cleaning process. 50 layers of Ge dots with Si spacer layers were epitaxially grown on the surface without texture and were etched by an HF/HNO_3 solution [4]. Finally, the SiO_2 films were removed using an HF solution. To focus on the optical properties, we used a solar cell geometry with no electrodes. 70-nm ITO layer and 140-nm Al layerwere formed at the front and back sides, respectively, as a solar cell geometry. For comparison, we fabricated a FS photonic nanostructure without a BS microtexture [Fig. 1(b)].

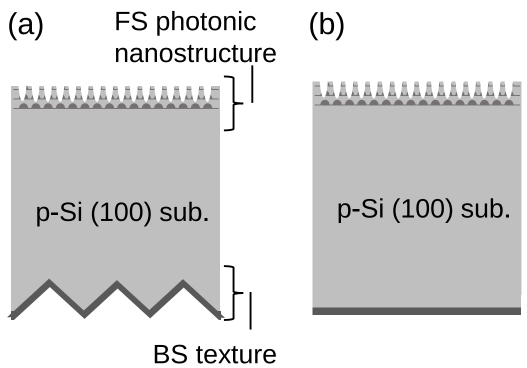

Fig. 1 Schematic illustration of (a) the double-side textures using front-surface (FS) photonic nanostructure and (b) the FS photonic nanostructure without back-surface (BS) textures.

3. Results and Discussions

To investigate the impact on light management, we measured the fundamental optical properties. Figures 3(a)-3(c) show the reflection of the double-side textured Si wafers with ITO and Al layers and the transmission and absorption spectra of the samples without ITO and Al layers. The spectra were measured with the incident light directed into the FS photonic nanostructure. In the Si wafers with the FS photonic nanostructure and ITO layer, the reflectance in the 400–1000 nm regions decreases lower than 0.1. Number of incident photons on the structures can be increased by photonic nanostructure formation. The transmission in the near infrared region decreases in the Si wafer with BS texture, which indicates an increase in light trapping and is consistent with previously performed simulation results [8,9]. As a result, the absorption at 1200 nm exhibits a significant increase for the Si wafers with the BS texture. This result implies that the BS microtexture causes efficient light trapping and enhanced optical absorption in the near-infrared region.

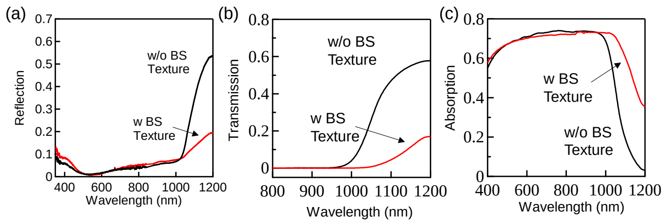

Fig. 2 Schematic illustration of (a) the double-side textures using front-surface (FS) photonic nanostructure and (b) the FS photonic nanostructure without back-surface (BS) textures.

Previous works indicate, however, that a part of the enhanced absorption in the near-infrared region may result from apparent optical absorption, such as parasitic absorption at the damaged surface in the absorbers and textures. To evaluate the true enhanced optical absorption, we performed photoluminescence (PL) excitation spectroscopy [10]. The samples were kept at 80 K during the PL measurements. The broad PL spectra appeared around 1550 nm, which are attributed to the light emission from Ge dots. Here, Ge dots that are not etched are used to probe the number of photocarriers generated by photon absorption in the near-infrared region because photocarriers generated close to the Ge dots are collected by the Ge dots and result in PL signals.

Figure 3 shows the spectrally integrated PL intensity in the 1500–1600 nm regions plotted as a function of the excitation laser wavelength ranging from 1000 to 1300 nm. In the double-side textured Si wafer, the PL intensity is larger than that in the sample with no BS texture. The fact that the PL intensity in the double-side textured sample is ~3 times larger than the sample without the BS texture at an excitation wavelength of 1200 nm indicates that the optical absorption is enhanced factor by ~3 at 1200 nm. Compared with the optical absorption enhancement, however, the enhancement of PL intensity is smaller than the enhanced optical absorption in Fig. 2(c), which indicates that a part of the enhanced optical absorption in Fig. 2(c) may originate from parasitic absorption. Detailed analysis is a next step of this work.

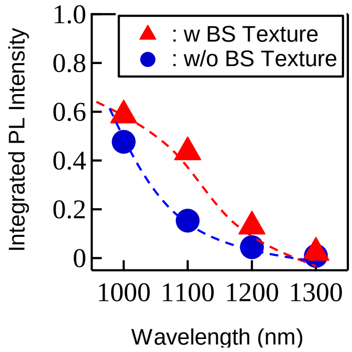

Fig. 3 Spectrally integrated PL intensities in the double-side textured and only FS textured Si wafers as a function of excitation laser wavelength.

4. Conclusions

We investigated light absorption enhancement due to light trapping in the double-side textured Si wafers with the front photonic nanostructure fabricated using quantum dot arrays. Our findings show that the double-side texture shows a significant light absorption enhancement in the near-infrared region.

Acknowledgements

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