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Broadband and multi angle enhanced antireflection of silicon solar cells by compound random nanostructures

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ABSTRACT

Recent research in nanostructures has shown the potential to effectively enhance light trapping of Si solar cells. In this article, it is demonstrated the decrease of optical reflection in silicon solar cells by a novel random nanostructure, which is combined of the Si random nanostructures (SiRNS) and nanoparticles. The compound random nanostructure is processed by inductively coupled plasma (ICP) and acid solution modification. The reflection of the SiRNS can be substantially reduced due to the graded refractive index. The adding of the nanoparticles to the SiRNS can further suppress the reflection within short wavelength ranges as a result of the excitation of micro-cavity effect and the scattering of light. The averaged reflection of the compound random nanostructured surface is under 6%, when the incident light angle is from 0° to 20°. Therefore, a broadband and multi-angle anti-reflection approach for solar cells is provided.

1. Introduction

Solar energy is considered as one of the most promising renewable energy in the future as it is clean and cheap. Solar cell is an important way for the efficient use of solar energy. Silicon has been widely used in solar cells because of its abundance, nontoxicity, and mature processing technology [1,2]. Previously, great attention has been focused on reducing cost and improving efficiency in the development of Si solar cells. Nanostructures have been proposed and demonstrated as an effective approach to enhance light trapping of Si solar cells [3–5],

Nanostructured surface can also result in the micro-cavity effect, surface plasmon effect, and light scattering to reduce reflection of Si solar cells within a broad wavelength range [5–7]. When the resonant wavelength of metals is located in the visible range, the metal nanostructure can cause parasitic absorption. However, the dielectric materials have no such parasitic absorption. In order to suppress reflection of Si solar cells, a variety of nanostructures for light trapping has been extensively investigated to enhance optical absorption, such as Si nanowire (SiNW) [8], Si nanoparticle (SiNP) [9] and grating [6,10]. Some nanostructures are simultaneously multi-angle antireflection [11,12]. Recently, nice absorption performances have been experimentally demonstrated in some structures [13,14]. In the previous study, periodic nanostructures have been paid much attention [15,16]. However, the experimental study on Si solar cell of the random nanostructure is rare despite of the existing consideration of random nanostructure [17,18]. Though the antireflection of these nanowires is distinct, the height of these nanowires is about 5 μm, with an aspect ratio of the height to the diameter which is too large. These nanostructures with longer nanowires are not suitable for solar cells application, which may cause high surface recombination and hinder the formation of the homogeneous antireflection coating. These nanowires may worsen the electrical properties of silicon solar cells. Therefore, in order to achieve efficient solar cell converters, it is necessary to look for and select an appropriate nanostructure.

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In this paper, a novel random nanostructure with intrinsic silicon substrate is developed for application to p–n junction silicon solar cells. Reflection is suppressed for a wide range of wavelengths and incident angles, which is essentially a compound random nanostructure of silicon random nanostructures (SiRNS) and nanoparticles. The SiNRS are realized by inductively coupled plasma (ICP) and the nanoparticles are obtained by a simple chemical method. By changing the experimental conditions, the SiRNS with different patterns are acquired. Then the optical properties of these SiRNS are investigated. It is found that the SiRNS can greatly reduce the reflection of the incident light. Furthermore, the adding of nanoparticles to the original SiRNS can significantly suppress the broadband and multi-angle reflection. Compared with other microstructured surfaces with longer nanowires, the hybrid microstructured surfaces presented in this work are more facile and feasible for applications to solar cells.

2. Experimental

2.1. Method and materials

The outline of the fabrication process of the random structure is shown in Fig. 1. P-type Si wafers with thickness of ~800 μm and resistivity of 1–50 Ω cm are used as substrates. A 50 nm thick silver film (Fig. 1a) is grown by magnetron sputtering on the silicon substrate. The sputtering pressure is 0.6 Pa, the sputtering power is 60 W. The thickness of Ag film is dominated by the sputtering time, which is called as time monitoring method. The samples with Ag film are placed in atmosphere furnace, which is vacuum. The sample with Ag film is placed in the controlled atmosphere furnace with vacuum. The temperature of the controlled atmosphere furnace is heated to 300 °C with a heating rate of 10 °C/min and kept 60 min, then the controlled atmosphere furnace is cooled naturally to room temperature. A monolayer of random silver nanoparticles 400 nm is formed on the top of the silicon substrate (Fig. 1b). The size of silver nanoparticles is about 400–500 nm. These silver nanoparticles are then used as an etch-mask during an inductively coupled plasma (ICP) process, since the etching rate of Ag is much lower than that of silicon. The dimensions of silver nanoparticles can be adjusted through the annealing conditions. Random nanostructure with silver nanoparticles (Fig. 1c) can be obtained through ICP, where the etching gas is SF_6. The samples should be fixed with high vacuum grease. The patterns of silicon nanostructured surfaces depended on the inductively coupled plasma etching conditions, for instance, the etching time, the etching power, the reaction chamber pressure and SF_6 flow. Finally, the samples (Fig. 1d) can be cleaned with hydrogen nitrate (65% HNO_3) and de-ionized (DI) water.

The morphologies of the samples are analyzed utilizing field emission scanning electron microscope top views (SEM). The optical properties of the samples are assessed with spectral reflection by Cary5000 UV–visible–infrared spectrophotometer (UV–V–NIR). During the measurements, an integrating sphere is used to collect any light emerging from samples.

2.2. Surface morphology

The morphology of silicon is affected by the etching power (radio frequency (RF) power) and etching time. Three samples with random silver nanoparticles on 200 μm silicon substrate are selected for the experimental study and the random silver nanoparticles are obtained under the same experimental condition. These samples are etched under different etching conditions, in which the RF power is 400 W/100 W, 200 W/50 W and 100 W/25 W, respectively. The etching time is 60 s, and the etching gas is SF_6. Fig. 2 shows two dimensional scanning electron microscope (SEM) images of the patterns of three samples after cleaning. The different SiRNS can clearly be observed. The reason of which is the etching rate reduces with the decrease in RF power. These nanostructures are inhomogeneous due to random

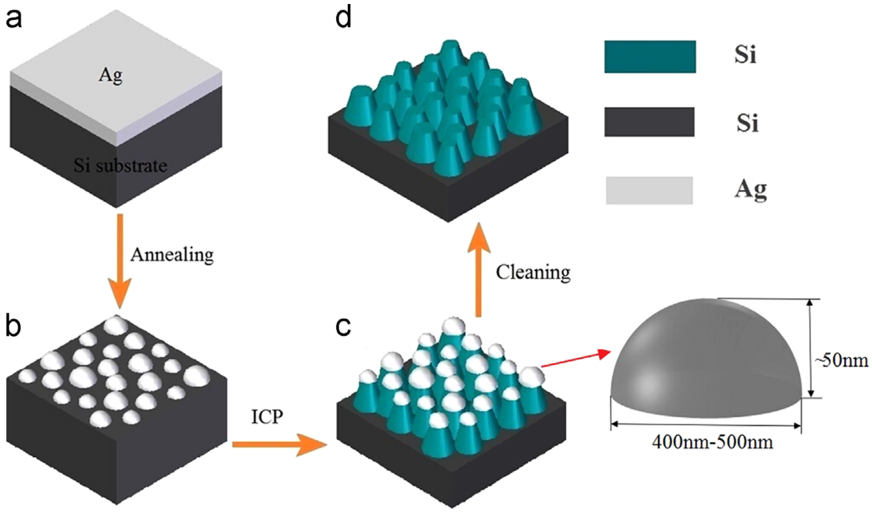

Fig. 1. Schematic illustration of random nanostructure formed: (a) 50 nm thick silver film deposited on the Si substrate, (b) random silver nanoparticles after annealing, (c) nanostructures with Ag nanoparticles after inductively coupled plasma (ICP), and (d) silicon random nanostructures after cleaning with hydrogen nitrate (65% HNO_3) and DI water.