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Enhancement of silicon-wafer solar cell efficiency with low-cost wrinkle antireflection coating of polydimethylsiloxane

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ABSTRACT

A low-cost antireflection (AR) coating of polydimethylsiloxane (PDMS) with wrinkle surface structure is demonstrated. The surface modulations with controllable amplitude and period are experimentally performed by plasma surface oxidation of a pre-stretched PDMS followed by removal of the applied mechanical strain. The period and the aspect ratio of the PDMS wrinkle are dependent on plasma treatment time in the process of surface modification. Compared with the solar cell without a wrinkle coating, the demonstrated PDMS wrinkle coating can improve the efficiency of actual commercial silicon-wafer solar cells, especially at large angles of incidence. Intriguingly, the all-day average relative efficiency of the cell with PDMS wrinkle is improved by approximately 13.6%.

1. Introduction

Solar energy as one of renewable energy resources is popular because of safety, cleanliness, non-pollution and inexhaustibility. In order to meet a sizeable part of the world's energy demand, an increasing number of researchers have been attracted to explore various solar cells to convert solar radiation into electrical energy, such as crystalline Si (c-Si) [1,2], amorphous Si (a-Si) [3], CdTe [4,5], GaAs [6], organic [7,8] and perovskite solar cell [9], and so on. Since the c-Si wafer solar cells have many advantages of high power conversion efficiencies, long lifespan, reliable performance, and proven manufacturability, they remain in the most widespread use in the photovoltaic industry [10]. One of considerable progress in c-Si photovoltaic (PV) technology is to fabricate textured structures on the surface of silicon solar cell, which is useful for the efficiency improvement of solar cells. A rich variety of optical structures on the front and/or rear surfaces of c-Si cells, such as pyramid [11], inverted pyramid [12], subwavelength grating [13], nanowire array [14], biomimetic and other nano/micro-structures [15,16], have been presented to increase the light-harvesting in PVs of c-Si. However, defects and high recombination rates are induced at an increased interface if the homogeneity of the layer thickness is not preserved [9,34].

On the other hand, the optical surface of solar cells with microstructure needs to be permanently protected by encapsulation, for the sake of providing and maintaining a transparent physical isolation from the exterior environment. In the last two decades, to improve broadband light trapping capability of solar cells and reduce the reflection loss, much attention has been paid to fabricate antireflective coatings with different surface texturing structures, such as nanocones [17], nanograting [18], pyramids [19], nanopillar [20], nanodome [21], nanotube [22], microlens array [23,24], and so forth. These surface textured structures on the antireflection (AR) coating are generally fabricated using some traditional processing technique, for example, nanoimprint [25], etching [20], interference lithography [26], self-assembling [27], laser structuring [28]. As one of them, nanoimprint method is widely used because of its simple fabrication [25]. However, not only the master molds are expensive and difficult to fabricate, but it is easy to be damaged in the process of stamp.

In contrast, wrinkles are self-organizing responses to linear and nonlinear elastic instabilities, and large-area wrinkles can be easily formed at low cost [29–31]. The wrinkle can effectively localize and trap light and consequently the efficiency of polymer thin film solar cells is improved [32]. Polydimethylsiloxane (PDMS) with high transparency in visible wavelength (300–800 nm) has been used to manufacture wrinkles thanks to reversible and repeated deformation without permanent distortion or relaxation of features [33]. A variety of PDMS wrinkle patterns have been demonstrated [34–36]. The wrinkles based on PDMS can be directly fabricated using a surface modification technology without master molds [37,38]. In this work, a novel method based on an ordered surface wrinkle of the PDMS is proposed to

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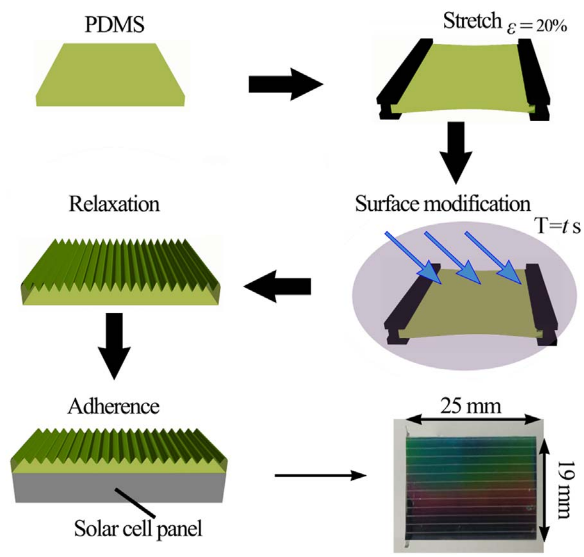

Fig. 1. Fabrication procedures of a solar-cell antireflective coating of PDMS with an ordered wrinkle and encapsulation of solar cell.

enhance the efficiency of commercial silicon-wafer solar cell. The surface wrinkle AR coating of PDMS is fabricated by plasma surface modification [39,40]. The experimental results show that the efficiency of the cell with a PDMS wrinkle AR coating is improved, especially at large angles of incidence, compared with the corresponding cell with epoxy resin polymer film.

2. Experimental details

The fabrication of the solar cell with PDMS wrinkle AR coating was divided into two steps: (i) fabrication of PDMS wrinkle AR coating and (ii) the preparation of solar cell.

2.1. Fabrication of PDMS wrinkle AR coating

The fabricated procedures of a solar-cell antireflective coating of PDMS with an ordered wrinkle were shown in Fig. 1. PDMS monomer (GE RTV 615 component A) and its crosslinking agent (GE RTV 615 component B) with a weight ratio of 10:1 were mixed, and then the mixture was degassed in the vacuum drying oven and baked at 80 °C for 8 h. After cured, the rectangle PDMS specimens with an area of 60 mm × 20 mm were cut with a razor blade and mounted to strain stage. Uniaxial strain was induced by clamping the sample extremities and stretching to 20% along the long dimension. Surface modification was carried out in an ion-beam etching device (ICP-5100, Chuangshiweina Ltd., China). The work electrode power and vacuum degree of the ion-beam etching device were 200 W and 5×10^{-3} Pa, respectively, and the reaction cavity was not inflated with extra oxygen throughout the process [41]. A top oxidized thin layer on the PDMS slab was formed, and the thickness and elastic modulus of the top layer depend on the exposure time and power [40]. Finally, the mechanical strain was removed and an ordered wrinkle film emerged on the PDMS surface. By tuning the treatment time with a fixed power of 200 W, the oxide layer thickness and modulus were adjusted and thus the pattern period and aspect ratio were directly controlled.

2.2. Preparation of the solar cell

The bare c-Si solar cell panel was bought from a commercial silicon-wafer solar cell company (Wuxi Suntech Power Co., Ltd). Firstly, the surface cleaning of the cell panel and glass substrate was performed. The cleaning consisted of three steps of ultrasonic 2 min dips in deionized water, alcohol, and acetone. Then, the cell panel was adhered to the glass substrate to avoid its fragility. Successively, a two-component epoxy resin (prepolymer 2:1 by mass base to crosslinking agent) was dropped on the surface of the solar cell panel which was placed on a 100 °C baked stage and the epoxy resin gradually spread out on the surface. After the epoxy resin cured, a PDMS slab with wrinkles was adhered to the surface of epoxy resin. The epoxy resin here is to fill interspaces between finger electrodes and to increase adhesive force between PDMS slab and the cell panel.

2.3. Characterization

To characterize the structures of surface wrinkles, the detailed two-dimensional surface topographies of the fabricated PDMS wrinkles were measured using an atomic force microscope (AFM; Park Systems) in non-contact mode. Furthermore, the reflectivity measurement of a c-Si solar cell with a wrinkle AR coating were achieved using a LAMBDA™ 1050 UV/Vis/NIR spectrometer along with 150-mm integrating sphere (PerkinElmer, Inc., Shelton, CT USA), and also solar cell *I-V* curves were measured under AM1.5 1 Sun illumination using a Newport Oriel PVIV Station.

3. Results and discussions

The wrinkle structure parameters are in connection with plasma treatment time and power as well as the stretched length of the PDMS slab. In following experiments, work electrode power and stretched length of 20% are kept unchanged. Fig. 2(a) and (b) show PDMS wrinkle AFM images at two plasma treatment time of $t = 60$ s and $t = 90$ s. It can be found that the wrinkle period $p = 950.0$ nm and depth $h = 253.7$ nm at $t=90$ s treatment time are larger than $p = 679.7$ nm and $d = 179.8$ nm at $t = 60$ s Fig. 2(c) shows the variation of both period and depth of the wrinkle structure with the plasma treatment time, and Fig. 2(d) shows the dependence of the wrinkle aspect ratio γ ($= h/p$) on the treatment time. It is found that both p and h almost linearly increases with increasing t, while γ nonlinearly increases with t until reaching a plateau of $\gamma = 0.265$ approximately. Generally, the aspect ratio depends on the tensile pre-strain and the Young's moduli, given by [40]:

$$\gamma = \frac{1}{\pi}\left(\varepsilon - \frac{1}{4}\left(\frac{3E_s}{E_o}\right)^{2/3}\right)^{1/2} \tag{1}$$

$$E = E'(1 - \nu^2) \tag{2}$$

where ε, E' and ν are the tensile pre-strain, the Young's modulus and the Poisson's ratio, respectively. E_s and E_o denote the plane-strain moduluses of the top oxidized layer and the PDMS flexible substrate. Under the condition of the constant tensile pre-strain, the aspect ratio is related to the Young's modulus E_o of the top oxidized layer. E_o was increased only by increasing t in our experiment. When $t > 80$ s, the modulus E_o attains t_o the final value of the oxidized layer. Consequently, a plateau of the aspect ratio is demonstrated, as shown in Fig. 2(d). Additionally, error bars in Fig. (c) and (d) denote range of wrinkle structure under three-time separate experiments which indicate that the structures of wrinkle are quite uniform and reproducible.

Our aim is to improve the efficiency of solar cells by using the low-cost PDMS wrinkle AR coating. For a wrinkle AR coating, the period and aspect ratio are two important parameters, which can be comprehended according to grating equation:

$$np(\sin\theta + \sin\beta) = m\lambda \tag{3}$$

where n is refractive index of the propagating media after diffraction, p denotes the grating period, and m the diffraction order. θ is the incident angle and β the diffraction angle. Eq. (3) shows that a small grating period leads to a large diffraction angle, and light will be diffracted into