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Brilliant white polystyrene microsphere film as a diffuse back reflector for solar cells

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ABSTRACT

Inspired by the microstructures in brilliant white beetle scales, we prepared films composed of randomly distributed dielectric polystyrene (PS) microspheres by a coagulation method. It is found that the about 20-μm-thick microsphere films appear brilliant white, with up to 98% reflectivity in the visible and near-infrared (IR) range and excellent scattering properties close to the Lambertian reflector. The microsphere films were applied as back reflectors for silicon thin-film solar cells, and enhanced the short circuit current and conversion efficiency by 31.2% and 36.7% on average, respectively. The fabrication of the films is low-cost, simple and mild, which is applicable for mass production.

1. Introduction

In recent years, increasing attention has been paid to the brilliant white beetles, for instance, the longhorn beetle *Calothyrzamargaritifera*, owing to their about 10-μm-thick scale generating brilliant whiteness. The whiteness results from the multiwavelength scattering of random chitin particles [1]. Inspired by this mechanism, various types of white surfaces composed of random microstructures were prepared, *e.g.*, random silicon oxynitride nanowires [2], polymer nanofibers [3], micropillar clusters [4] and TiO_2 nanoparticles [5]. These white materials showed good reflectivity and were applied in LEDs, paper coatings, *etc*.

Particularly, these brilliant white materials may exhibit superior performances as back reflectors (BRs) that are critical for silicon thin-film solar cells. As the silicon absorber layer is thinner than 2 μm, a single pass of light is insufficient to capture the weakly absorbed photons. So efficient light scattering at a BR is highly desired to prolong the optical path length. Most BRs in silicon thin-film solar cells are microstructured silver or aluminum films which, however, cause parasitic absorption [6]. Therefore, alternative BRs of diffuse dielectric materials have been investigated, for example, white paint and TiO_2 nanoparticles [7–10]. White paint, although a better BR than aluminum, is disadvantageous because of a relatively low refractive index contrast between pigment and binder [7,8]. A BR of TiO_2 nanoparticles without binder can improve the performance of solar cells significantly [9,10]. However, these brittle inorganic oxide particle films suffer from poor mechanical strength and harsh fabrication conditions.

Herein brilliant white films composed of randomly distributed PS microspheres are prepared by a coagulation method under moderate conditions. The prepared films show very high reflectivity and excellent scattering properties close to the Lambertian reflector. The microsphere film is used as a BR for silicon thin-film solar cells, which significantly enhances the short circuit current (J_{SC}) and conversion efficiency.

2. Experimental

Monodisperse PS microspheres were synthesized by combining a hydrothermal process with a dispersion polymerization process as employed in our previous work [11], whose negative surface charges rendered them stably dispersed in ethanol/water solution. Then some de-ionized water was added to form a sphere concentration of 2 wt%.

By adding $CaCl_2$ to provoke the colloids agglomeration and then evaporating the liquid, a film of random distributed microspheres was prepared. The concentration of $CaCl_2$ depended on the diameter, surface potential and concentration of the microspheres [12]. Typically, 20 μL $CaCl_2$ solution (1 M) was added to 2 mL suspension of PS microspheres (diameter = 650 nm, surface potential = −35 mV). Then the suspension was sonicated for 5 min and drop-cast on a substrate. After the liquid evaporated completely at room temperature in 8 h, a film of randomly distributed PS

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microspheres was obtained. To enhance the strength, the microsphere film was heat-treated at 100 °C for 30 min. The film thickness could be controlled by the suspension volume and the microsphere concentration. Typically, 2 mL suspension with 2 wt% concentration forms a microsphere film with a thickness of ~20 μm and an area of 2.5×2.5 cm^2.

The silicon thin-film solar cells (Chengdu Xushuang Solar Technology) used possess an area of 2.5×2.5 cm^2. The intrinsic a-Si:H absorber layer is 300 nm thick. A PS microsphere film was prepared as the BR on the transparent rear contact.

The PS microsphere films were observed with a field-emission SEM (Quanta, Netherlands) and the thickness was measured by a surface profilometer (STIL, France). The strength of the films was characterized using a scratch tester (Bruker, Germany). The reflection and absorption were measured with a PerkinElmer Lambda 950 spectrophotometer equipped with an integrating sphere. The angular distribution of the reflecting light was measured by an in-house setup consisting of a laser ($\lambda = 632.8$ nm) and a power meter (Thorlabs, USA) fixed on a rotating beam. The J–V characteristics of solar cells were obtained by a semiconductor device analyzer (Agilent, USA) under AM 1.5 (100 mW/cm^2) illumination by an Oriel solar simulator.

3. Results and discussion

Fig. 1(a) shows a microsphere film with a thickness of 23 ± 2 μm and a sphere-diameter of 650 nm, which appears bright and white. Fig. 1(b) shows an SEM image of the cross-section of the microsphere film and the zoom-in view (Fig. 1(c)) reveals the random arrangement of microspheres, which is very similar to the internal structure of the beetle scale (Fig. 1(e)). The microspheres get slightly molten and stick to each other after heat treatment, while the edges of the randomly distributed microspheres without heat treatment are well-defined as shown in Fig. 1(d).

As the scratch tracks shown in Fig. 2(a), the microsphere film without heat treatment fails at the beginning of the track at the initial load of 0.2 N. For the heated microsphere film, no failure but plastic deformation and micro-conformal cracks are observed at first, and then large detached silicon regions appear at the load of 1 N, indicating the failing point (Fig. 2(b)). The load that causes film failure is much larger for the microsphere film with heat treatment than the one without, which confirms that the former is more robust. Meanwhile, the optical properties are not affected notably. All microsphere films discussed below are heat-treated.

Microsphere films with sphere-diameters of 350 nm, 520 nm, 950 nm and 1220 nm were also prepared, under the same condition with the 650 nm microsphere film discussed above. All the microsphere films show very high reflectivity at visible wavelengths, and the films with larger spheres also exhibit outstanding reflectivity in near-IR range as shown in Fig. 3(a). The reflectivity of the film with 950 nm microspheres remains about 98% across the whole visible and near-IR range, while the reflectivity of the film with 350 nm microspheres gradually decreases with increasing wavelength. We can see fluctuations in all the curves in Fig. 3(a), which is related to the Mie scattering of the microspheres.

The CIE chromaticity coordinates of x and y were obtained under standard illuminant D65 as shown in Fig. 3(b). The CIE coordinates of the microsphere films are close to the standard white point ($x = 0.3124$ and $y = 0.3290$) in the chromaticity triangle, indicating that the films are ultrawhite.

The angular distribution of the reflected light (Fig. 3(c)) reveals that the films with smaller microspheres have broader angular distribution than the films with larger ones. Since all the films are fabricated by the same volume of suspension and concentration of microspheres, there are more microspheres in films with smaller microspheres than those with larger microspheres. This indicates that a photon is scattered more times before escaping from the films with smaller microspheres. The angular distribution of the films with smaller microspheres (350 nm, 520 nm and 650 nm) approaches the Lambertian distribution. These results indicate excellent scattering capabilities of the microsphere films, which are far superior to the conventional metal-based reflectors.

Given the reflectivity at long wavelength, the film with 950 nm microspheres was chosen as a BR for solar cells. As shown in Fig. 4(a), the microsphere film enormously improves the absorption of the solar cell over long wavelength spectrum (> 550 nm), confirming the microsphere film as an efficient BR. Many of the photons

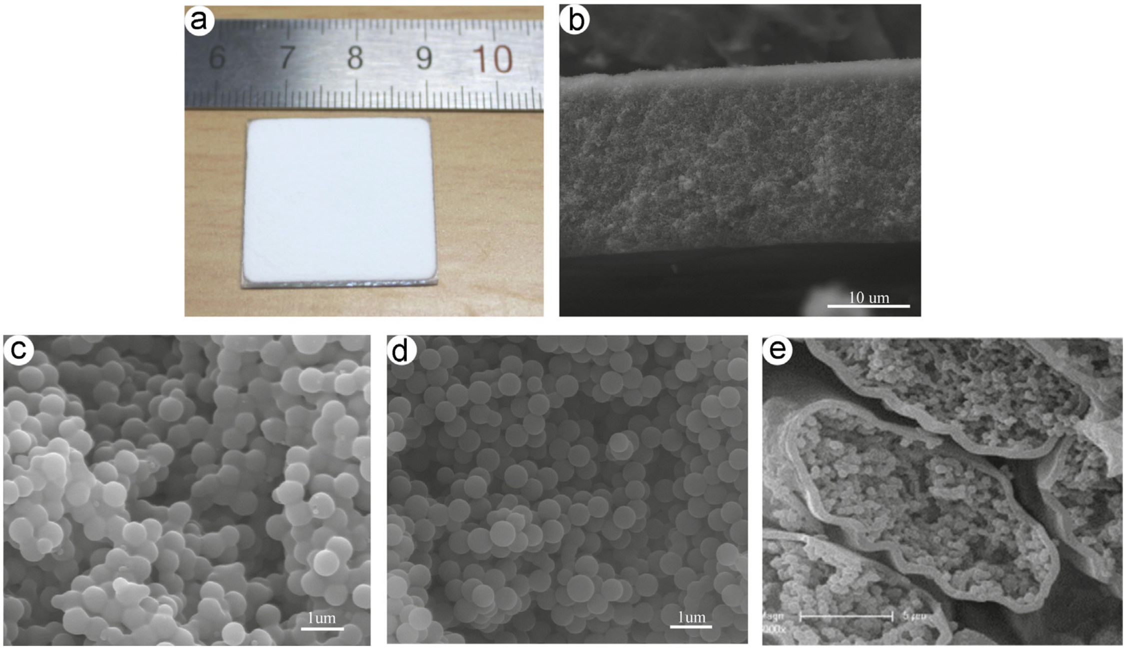

Fig. 1. (a) Picture of a microsphere film on a glass slide. (b) SEM image of the cross section of a microsphere film. (c) and (d) The zoom-in views with (c) and without (d) heat treatment. (e) SEM image of cross section of the beetle scale (reprinted from [1], with permission from Elsevier).