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Simultaneous realization of light distribution and trapping in micromorph tandem solar cells using novel double-layered antireflection coatings

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ABSTRACT

Implementing antireflection (AR) coatings in micromorph tandem solar cells is a challenging process in which not only more sunlight should get conducted into the cells, but also the current matching between subcells should either be maintained or get improved. In this work, the novel double-layered AR coatings were prepared on either one side or two sides of glass superstrates using hybridized hollow silica nanosphere (HSN) sols. As a result of improvement in light distribution via double-layered AR coatings, the current difference between the top and bottom subcells was decreased to be 0.05 mA/cm^2, much smaller than that of untreated cells, 0.33 mA/cm^2. Furthermore, the cells grown on the two-sided AR coated superstrates demonstrated the largest increases in current densities of top and bottom subcells, 4.20% and 7.53%, respectively, which were much higher than those of the cells on one-sided AR coated superstrates. The underlying origin was ascribed to the better light trapping induced by multiscale texturing at front boron-doped zinc oxide (BZO) electrodes, which resulted from the conformal growth of BZO on HSNs with unique surface morphologies. The findings provided a practical way to simultaneously realize light distribution and trapping using the two-sided AR coated glass superstrates without any amendment of layers inside micromorph tandem solar cells.

1. Introduction

Antireflection (AR) coatings on glass are widely applied to suppress reflections in single-junction solar cells. For example, porous silica AR coatings [1–4] are coated on solar glass to minimize Fresnel reflections at the interface between air and solar glass. The AR coatings have a refractive index around 1.23 and fulfill the relationship of $n = \sqrt{n_{air} n_{glass}}$ (generally, $n_{air} = 1$ and $n_{glass} = 1.52$), leading to a significant increases in short-circuit currents. As reported in the literature [4], a relative increase of 3% was achieved using the electrospinned porous silica AR coatings. In addition, the multilayer and biomimetic nanostructured AR coatings were also developed for suppressing reflections in broadband, which increased the current by 3.1% for the thin-film CdTe solar cells [5] and 7.06% for the photovoltaic modules [6], respectively.

As compared with AR coatings for single-junction solar cells, the design and realization are more challenging if the AR coatings are utilized in series interconnected multi-junction solar cells. Besides a larger required AR bandwidth for multi-junction solar cells, the current matching of subcells should be maintained or even improved. Thus, the AR coatings should couple as much light into the cells as possible and properly distribute the light to each subcell for maximizing the power conversion efficiency [7,8]. Thus far, most efforts have been made on the realization of broadband AR coatings for coupling more light into solar cells [5,6,9–13], but few reports study the roles of AR coatings in tailoring the current densities of subcells, which was, generally, achieved by changing the thickness of corresponding active layers or using intermediate reflectors [8,14,15].

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To properly distribute the incoming light to each subcell using AR coatings, the coatings should have the capability to selectively suppress the reflections at different wavelength regions. The conventional single-layered quarter-wave AR coatings have one reflection minimum, which is located at the central wavelength; the double-layered quarter-half-wave AR coatings have two reflection minima (often called "W"-coatings), which appear on both sides of the central wavelength [16–18]. Thus, the reflection minima are determined by the central wavelength and there is no much degree of freedom to tailor the AR wavelengths. To freely choose the AR wavelengths, the refractive indices of thin films in AR coatings must be tailored over a large range. Recently, we reported a means to precisely tailor the refractive indices of silica thin films from 1.10 to 1.45 [19] via the hybridization of hollow silica nanospheres (HSNs) with acid-catalyzed silica, which could be building blocks for the AR coatings aiming at specific AR wavelengths.

To study the relationship between AR properties and current matching of subcells, we designed and fabricated two series of double-layered AR coatings using the hybridized HSNs. The two series of AR coatings had different optical thicknesses, and the effects on current matching were systematically studied. The AR coatings were deposited on one side or two sides of glass superstrates. The more significant improvement in current density was observed from the solar cells grown on two-sided AR coated glass, which was beyond the estimated increases and the underlying origin was studied. These findings reveal that light distribution and trapping could be simultaneously achieved without any amendment of the growth of active layers, intermediate reflectors, and transparent conducting electrodes inside micromorph tandem solar cells.

2. Experiments

2.1. Preparation of novel double-layered AR coatings

Two series of double-layered AR coatings were prepared to study the effects on current density improvement and current matching of subcells in micromorph solar cells. One series of AR coatings was designed to preferably suppress the reflection at the short wavelengths, which was named the type SW. Similarly, the other series of AR coatings, the type LW, was effective to suppress the reflections at the long wavelengths. They were dip-coated on one side or two sides of glass superstrates (Schott AF45 glass with a thickness of 0.5 mm) using a SYDC-200 dip coater. For both the type SW and LW double-layered AR coatings, the bottom layers were derived from the HSNs sols hybridized with 20 g acid-catalyzed silica sols (i.e., the fabricated films contain 81.67% acid-catalyzed silica) and the top layers were prepared using the HSNs sols hybridized with 1 g acid-catalyzed silica sols (i.e., the fabricated films contain 18.21% acid-catalyzed silica). Correspondingly, the refractive indices of the bottom and top layers were 1.37 and 1.18 at a wavelength of 600 nm, respectively, which were retrieved from the spectroscopic ellipsometry measurements of these thin films coated on silicon substrates. The detailed process about the hybridized sol–gel coatings could be found in our previous report [19].

2.2. Preparation of micromorph solar cells

Five kinds of superstrates were used for the growth of micromorph solar cells: bare glass, one-sided type SW coated glass, one-sided type LW coated glass, two-sided type SW coated glass, and two-sided type LW coated glass. Correspondingly, the fabricated solar cells were designated as the cells I, II, III, IV, and V, respectively.

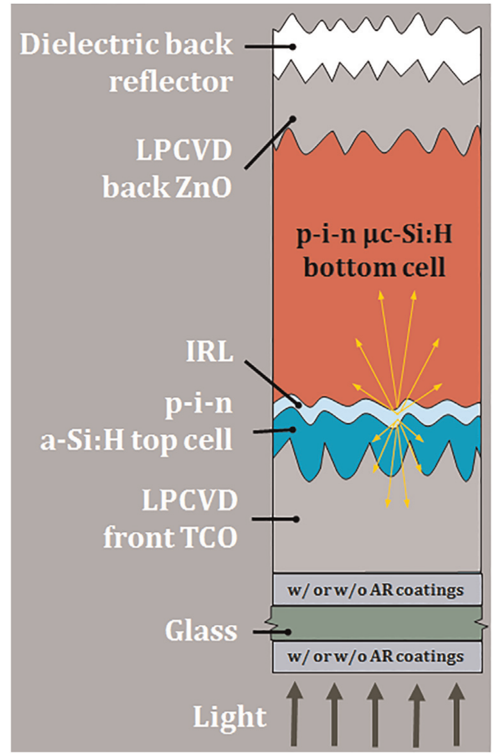

Fig. 1. Graphical representation of the micromorph solar cells.

A graphical representation of the micromorph solar cells is shown in Fig. 1. First, a boron-doped zinc oxide (BZO) film with pyramidal surface features was deposited as a front electrode by low pressure chemical vapor deposition (LP-CVD) at 180 °C. Then, an argon plasma surface treatment was performed for 4 min on the rough BZO surface to optimize the morphology for the growth of the cells. The micromorph tandem cells were fabricated by plasma enhanced chemical vapor deposition (PECVD) in a dual-chamber research-scale system. The solar cells consisted of an a-Si:H top cell with an intrinsic layer thickness of 200 nm and a μc-Si:H bottom cell with an intrinsic layer thickness of 1.1 μm. A resistive SiO_x intermediate reflector [14,20] was introduced between the a-Si:H top and the μc-Si:H bottom cells to limit local current drains caused by the roughness of the superstrate and reflect part of visible light back into the top cell. The back electrode BZO with the same thickness of 2.3 μm as the front electrode BZO was deposited as described above, but without the plasma treatment. The cells were finally patterned to three 5×5 mm^2 cells by lift-off and SF_6 reactive ion etching. The details in the micromorph solar cells preparation could be found elsewhere [21].

2.3. Characterization

The wavelength-dependent ellipsometric parameters, Ψ and Δ, were measured using a spectroscopic ellipsometry (M2000-DI, J. A. Woollam Co.) at three incident angles of 55°, 65° and 75° and the wavelength ranging from 300 to 1700 nm. The thicknesses and refractive indices were determined once the Ψ and Δ ellipsometric parameter curves were well fitted to a Cauchy model [22]. The optical transmittance and reflectance were measured by an ultraviolet–visible–near infrared (UV–vis–NIR) spectrophotometer (Lambda 950, PerkinElmer). A scanning electron microscope (SEM, Hitachi SU-70) was used to observe the surface morphologies.