Nanometer SiO_2 Antireflection Coating for Solar Modules

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***Abstract*—In the applications of solar cells, reflection is an unwanted loss process. Using antireflective solar glass can improve the generating efficiency of solar cells. Here the design, synthesis, modification, and characterization of the nano antireflective film for solar modules are reported. Nanometer SiO_2 antireflection coating solution was prepared by Sol-gel method. Porous membrane with visible light transmittance of up to 98.2% can be derived from base-catalyzed sol. With modification of the mechanical durability of the samples, the transmittance was improves to 97.43%. Average over wavelength range from 400 to 800 nm, the reflection losses were reduced to only 3.44% by applying the nanometer SiO_2 antireflection coating to the cover glass, that is , the AR coating achieves a transmittance enhancement of 5.6% comparing to the original glass. Uniform antireflection and high scratch have been achieved.**

Keywords-antireflective coating; porous SiO_2 film; solar glass; Sol-gel

INTRODUCTION

Owing to the abundance of solar energy on the earth, and the minimal environmental impact of photovoltaic energy conversion, photovoltaic technology and PV market are attracting more and more concerns of the public. Considering the two primary factors of improving the photovoltaic conversion efficiency and lowering the cost of photovoltaic power generation, improving the light transmittance of solar modules in greater range is an effective method to shorten the payback period.

Antireflection coatings are an indispensable component to reduce or suppress Fresnel reflection losses.[1] Conventionally and ideally, a single layer antireflection coating with an optical thickness equal to λ/4 should have refractive index given by

(1)

But due to the unavailability of materials desired, the performance of such λ/4 AR coatings deviates from the optimum.[2] While the porous AR coating is possible to tune the radiative properties of an optical film to virtually any value needed in applications.

Besides, driven by the demand for AR coating with not only better AR characteristics in solar cell's response spectral range, but also higher hardness, better scratch resistance and weather resistance, many ways have been investigated so far, including dielectric interference coatings, surface texturing, adiabatic index matching and scattering from plasmatic nanoparticles.[3]

In order to analysis the radiative properties of particle dispersion system, effective field theory (EFT) is proposed, which is a type of approximation to find the refrective index of the porous film here. It is proved that when the size of dispersed particles is far smaller than the wavelength of incident radiation, the predictions of EFT models shows good agreement. While using EFT models to analyse the radiative properties can effectively avoid solving the radiative transfer equations with complex numerical calculation and boundary conditions. The results indicate guidelines for designing the nanocomposite materials with desired optical properties.

In this paper, the radiative properties of the nano-gel and porous film were investigated firstly. Six effective field theory models are applied to predict the effective refractive index of the porous film and further to direct the design of the nano-gel and the porous AR film. In experiments, nanometer SiO_2 antireflection coating solution was prepared by Sol-gel method, porous SiO_2 film was coated on the surface of the glass by dip coating process, then heat treated to make the coating and the glass substrate firmly combined. Antireflective glass for solar photovoltaic modules was successfully fabricated with high transmittance in solar cell's response spectral range. And with effective modification of the nano-gel, high hardness and good scratch resistant ability was derived with minimal decrease in the optical properties of the AR coating.

EXPERIMENT

The radiative properties of the nano-gel and porous film were investigated firstly. Six effective field theory models including: (1) Maxwell-Garnett; (2)Bruggeman; (3)Lorentz -Lorenz; (4)Parallel; (5)Series; (6)VAT; are applied to predict the effective refractive index of the porous film. The applicability of these models is investigated for nano porous thin films with different diameters and various porosities.

Glass samples with antireflection coatings are prepared by Sol-gel method. Uncoated substrates were handled carefully to prevent contamination. Before coating, the substrates (K9 glass) were soaked in acid for 20min, then in ethyl alcohol for 30min. After flushed with DI water and dried, the substrates were ready for dip coating. The base-catalyzed SiO_2 sols were prepared with tetraethyl orthosilicate (TEOS). The principal reactions are mentioned below:

The nanometer SiO_2 sols was prepared with TEOS as precursor, absolute ethyl alcohol as solvent, and ammonium hydroxide as catalyst. TEOS, ethyl alcohol, and ammonium hydroxide were mixed, mechanical stirred, and aged at some temperature. The effect of different factors, such as aging temperature, aging time, the amount of catalyst, pH, H_2O, and the mole ratio of ethyl alcohol on the properties of the nanometer SiO_2 sol. were carefully studied. And stable sols with controlled particle size were obtained.

With the previous mentioned base-catalyzed sol., we got AR coating samples with excellent visible light transmittance, but poor wear resistance and low hardness. Polysiloxane was doped to modify the base-catalyzed sol. It was prepared with TEOS as precursor, absolute ethyl alcohol as solvent, and HCI as catalyst. TEOS, ethyl alcohol, and HCl were mixed, mechanical stirred, pH was adjusted to 3~4, and the collosol was aged for 7-10days at room temperature.

The Polysiloxane collosol with volume fraction of 0, 2%，5%，8%，16% were added to the base-catalyzed sol for modification. After being fully stirred, and standing for some time, the collosol was ready for dip coating. The particle size of the nanometer SiO_2 sol and its distribution was detected with Malvern Zetasizer Nano ZS90.

The coating sol was filtered with 0.2μm millipore filter. The coating process was operated in a constant temperature dip coating machine. The pulling speed was between 90-190mm/min, and the temperature was 25°C.

The coated glasses were baked at 200℃ for 10min, and sintered at 500℃ for 30 min. Shimadzu UV-3600 plus was used to find out the characteristic of spectrum of the coated glass samples.

Results And Discussion

Radiative properties of the nanometer porous menbrane

Adjusting the porosity is effective to control the apparent optical properties of the thin films. For the participate medium, the radiative properties can be predicted by solving the radiative transfer equation, or using the effective field theory models. For the particle size of the SiO_2 sol is far smaller than the wavelength of incident radiation. Using EFT models is easy and presents strong engineering applicability.[4]

The Maxwell-Garnett theory was first developed to model the effective electric permittivity of heterogeneous media consisting of spheres arranged in a cubic lattice structure within a continuous matrix.[5] The effective dielectric constant is expressed as

(2)

Where and are the dielectric constant of the continuous and dispersed phases, respectively.is the porosity.

Bruggeman[6] model was proposed for participate medium with dispersed phase volume fraction larger than λ/6，that is, larger than 52%, which is more suitable for nano SiO_2 AR coating.

(3)

The Lorentz-Lorenz[5] model gives the effective index of refraction as

(4)

Two simpler models are the parallel and series models.[5]The parallel model gives a linear relationship between the effective radiative properties of the porous thin film and the radiative properties of the continuous /dispersed phases.

(5)

While the series models gives

(6)

Volume averaging theory(VAT)[7-9] was proposed for dispersed domain of arbitrary shape in a continuous matrix.

(7)

(8)

The index of refraction index can be expressed in terms of the real part of their dielectric constant , and of their electrical conductivity as[4]

(9)

Where is the wavelength of incident radiation, is the speed of light in vacuum, and is the permittivity of free space.

The predictions of these six models are present in Figure 1. Different models show agreement with each other. The predictions of the series models are lower, while the predictions of VAT models are higher. It is shown that by adjusting the porosity, the effective refractive index of the nano SiO_2 porous thin film is continuously adjustable.

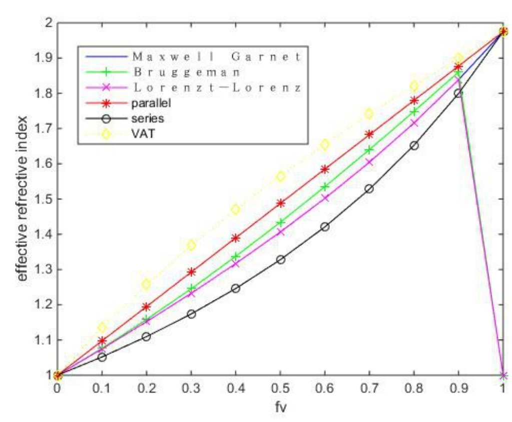
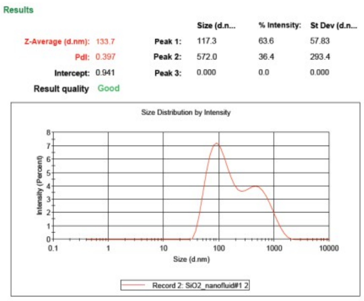
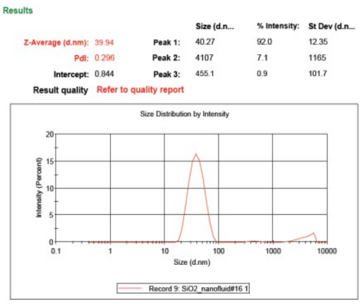


Figure 1. Effective refractive index versus volume fraction of particles for the porous thin film



(a)



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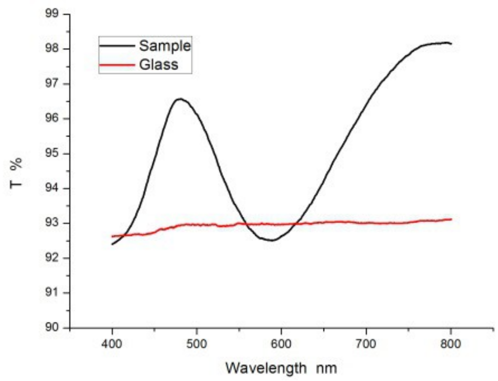


(c)

Figure 2. (a), (b) measured particle size of different sol. Samples; (c) transmittance of the original glass and the samples with AR coating.

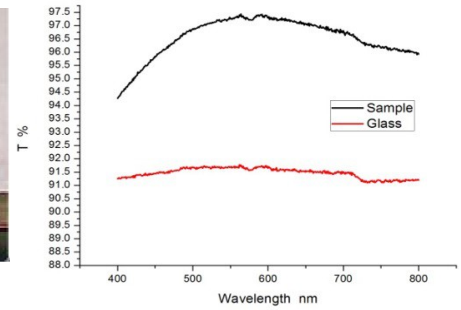
Coating derived from base-catalyzed sol.

In the preparation experiments, the effect such as aging temperature, aging time, amount of catalyst, pH, H_2O, and the mole ratio of ethyl alcohol on the properties of the nanometer SiO_2 sol were studied. Some results from Malvern Zetasizer Nano ZS90 can be found in Fig, 2. Stable sols with controlled different particle sizes were obtained. Figure 2(c) shows that, the coated glass samples with visible light transmittance of up to 98.2% can be derived from the base-catalyzed sol. Average over wavelength range from 400 to 800 nm, the reflection losses are reduced to only 4.88% by applying the AR coating. There is significant promotion over some wavelength range.

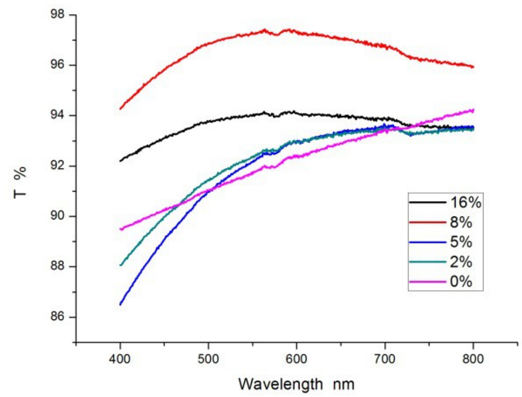
Coating derived from modified sol.

With the previous mentioned base-catalyzed sol., we got AR coating samples with excellent visible light transmittance, but poor wear resistance and low hardness. Polysiloxane was doped to modify the base-catalyzed sol. In the acid catalyzed doping sols, macromolecules of entangled linear or randomly branched chains were introduced to form a mutual adhesion, which resulted in higher viscosity and improvement of system stability. Besides, the film became more smooth, which results in better wear resistance and higher hardness. The Polysiloxane sol with volume fraction of 0, 2%， 5%， 8%， 16% were added to the base-catalyzed sol. The transmittance of the AR coated glasses with different doping rates is shown in Figure 3. It is shown that, with the doping ratio increased, the apparent refractive index could be adjusted, the visible light

(a)



(b)



(c)

Figure 3. (a) the AR coated glass (upper side coated), (b) transmittance of the original glass and the samples with doped AR coating; (c) transmittance of the samples with different doping ratios.

transmittance first increased and then decreased. The transmittance was improves to 97.43%. Average over wavelength range from 400 to 800 nm, the reflection losses were reduced to only 3.44% by applying the nanometer SiO_2 antireflection coating to the cover glass, that is, the AR coating achieves a transmittance enhancement of 5.6% comparing to the original glass.

Coating process

The coating process was operated in a constant temperature dip coating machine. The pulling speed was between 90-190mm/min, and the temperature was 25°C. The transmittance of samples coated with different lifting speed is shown in Figure 4. With faster lifting speed, which results in thinner coating, the transmittance increases at short wavelength, and decrease at long wavelength. Average over wavelength range from 400 to 800 nm, the transmittance of the sample with lifting speed 190mm/min achieves 96.5%.

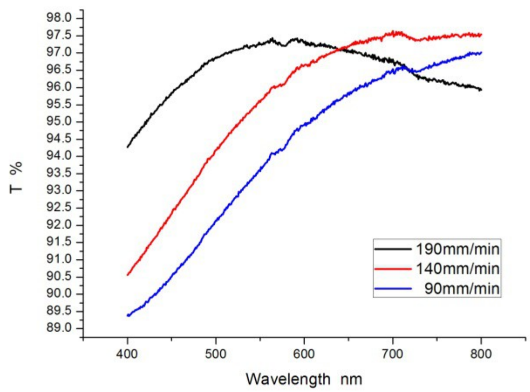


Figure 4. Transmittance of the samples with different lifting speeds.

Conclusion

In conclusion, we have demonstrated our design, synthesis, modification, and characterization of the nano meter SiO_2 antireflective film for solar modules. Nanometer SiO_2 antireflection coating solution was prepared by Sol-gel method. Porous membrane with visible light transmittance of up to 98.2% can be derived from base-catalyzed sol. With modification of the mechanical durability of the samples, the transmittance was improves to 97.43%. With the doping ratio increased, the apparent refractive index could be adjusted, the visible light transmittance first increased and then decreased. With faster lifting speed, the transmittance increases at short wavelength, and decrease at long wavelength. Average over wavelength range from 400 to 800 nm, the reflection losses were reduced to only 3.44% by applying the nanometer SiO_2 antireflection coating to the cover glass, that is , the AR coating achieves a transmittance enhancement of 5.6% comparing to the original glass. The nanometer antireflective solutions were stable. Uniform antireflection and high scratch have been achieved, which can be used in solar modules to promote the PV system efficiency.

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