Design of broadband and wide-angle antireflection for solar cells

Wenliang Wang (王文梁)[1*] and Honggang Hao (郝宏刚)[2]

[1] *Department of Physics, Nanchang University, Nanchang 330031, China*

[2] *College of Electronic Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China*

[*] *E-mail: W.L.wang@163.com*

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Antireflection coatings are very important for high-efficiency solar cells. An ideal antireflection structure should lead to zero reflection loss on solar-cell surfaces over an extended solar spectral range for all angles of incidence. Based on the optical thin-film theory, two multilayer structures are adopted as initial stacks in two conditions, respectively. With the aid of a conjugate graduate optimized method, the incident angles of antireflection coating are 0°–60°, the working wavelength range is 400–1200 nm, and two broadband and wide-angle antireflections are designed. The results show that they can all evidently reduce residual reflection.

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A solar cell converts absorbed photons into electrical charges. Ideally, a solar cell should absorb all useful photons. However, more than 30% of incident light is reflected back from the surface of single-crystalline Si solar cells because of the high refractive index of Si material. Antireflection coatings are therefore widely utilized to improve the conversion efficiencies of Si solar cells. An ideal antireflection structure should lead to zero reflection loss on solar-cell surfaces over an extended solar spectral range for all angles of incidence. Therefore, the development of a perfect broadband and wide-angle antireflection structure has been an important issue in solar-cell applications.

In theory, several methods have been presented to reach perfect antireflection. The first is the graded index antireflection structure[1−4], where the refractive index changes gradually from the top to the bottom. An extremely low reflection can be achieved over a broad spectral range for a wide range of incident angles in this kind of structure. However, the practical control of index profiles is very difficult, which is a limitation in its practical applications. The second is the textured microscale surface for omnidirection antireflection coatings[5−7], which is the most successful method used in all commercial single-crystal Si solar cells. However, the microscale surface texture involves anisotropic etching of the Si substrate, which does not apply to polycrystal Si and non-Si solar cells. The third is single or multilayer quarter-wavelength film stacks[8]. In solar-cell applications, such antireflection structure reduces reflectivity only in a limited spectral range under surface normal incident conditions at present.

In this letter, we design two broadband and wide-angle antireflections used in different conditions, which can operate at incident angles of 0°–60° and over a wavelength range of 400–1200 nm. The designs are based on the optical thin-film theory, with the aid of an optimization method.

The theory of antireflection coatings has been widely discussed in the literature. Based on many design results, Willey *et al.* gave an experiential formula to estimate the minimum average residual reflection[9]

$$R_{\mathrm{AVE}}(B,L,T,D)\% = (4.378/D)(1/T)^{0.31} [\exp(B-1.4)-1](L-1)^{3.5}, \quad (1)$$

where, $B = \lambda_{\max}/\lambda_{\min}$ is the bandwidth of antireflection, $\lambda_{\max}$ and $\lambda_{\min}$ are the maximum and minimum working wavelengths, respectively. L is refractive index of the uppermost layer, $T = \sum_i nd/\sqrt{\lambda_{\max}\lambda_{\min}}$ is the total optical thickness of the multiplayer stack, and D is the difference in refractive index between two materials that are used in the interference stack with maximum and minimum indices, respectively. The uppermost layer is an exception.

With respect to the design of antireflection over a super broadband wavelength range, there is no very simple and effective method that can be used, and optimization technology is necessary. To obtain a good design that can satisfy the actual requirement, the starting design is important. Baumeister *et al.* gave the following principles to construct the starting structure[10].

Firstly, the central wavelength should be $\lambda_0 = 2(1/\lambda_{\min} + 1/\lambda_{\max})^{-1}$.

Table 1. Refractive Indices Used in the Calculation

Wavelength (nm)	Si	MgF_2	TiO_2
400	5.1099	1.3903	2.5440
500	4.2583	1.3850	2.3570
600	3.9647	1.3800	2.2890
700	3.9133	1.3768	2.2620
800	3.8687	1.3762	2.2500
900	3.8124	1.3756	2.2495
1000	3.7677	1.3750	2.2490
1100	3.7123	1.3745	2.2485
1200	3.6775	1.3740	2.2480

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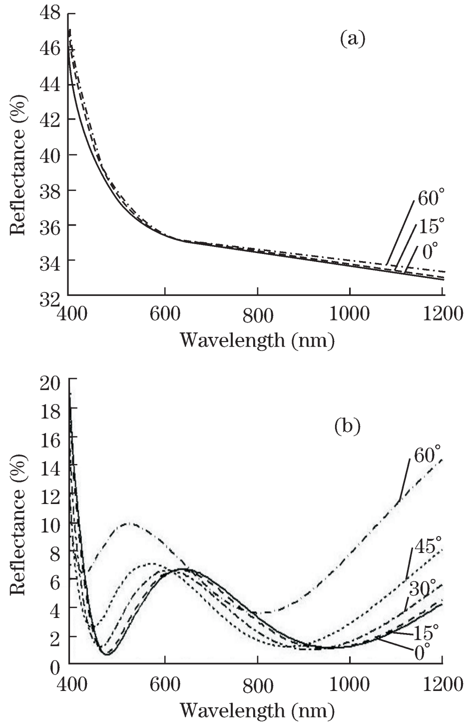

Fig. 1. Reflection curve of the solar cell (a) without antireflection and (b) with antireflection when the incident medium is air.

Table 2. Optimal Parameter of the Design

Layer	Substrate	1	2	3	4	Media
Material	Si	TiO_2	MgF_2	TiO_2	MgF_2	Air
Thickness (nm)		60.32	29.66	6.25	63.46	

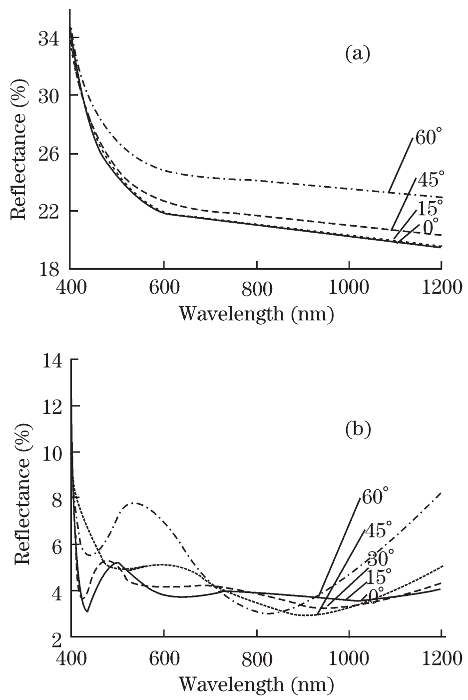

Fig. 2. Reflection curves of the solar cell (a) without antireflection and (b) with antireflection. when it is encapsulated by silicon glue.

Table 3. Optimal Parameter of the Design When the Solar Cell is Encapsulated by Silicon Glue

Layer	Substrate	1	2	3	4	5	Media
Material	Si	TiO_2	MgF_2	TiO_2	MgF_2	TiO_2	Glue
Thickness (nm)		74.40	33.80	25.03	63.72	8.94	

Secondly, the coating material of the uppermost layer should have a dominant influence on the residual reflectance obtained for a given (broad) bandwidth.

Thirdly, there should be at least one thick film layer. The multiplayer structure must be a combination of some thin and thick films.

The super broad spectrum antireflection should be used in a solar cell, which should lead to zero reflection loss on solar-cell surfaces over an extended solar spectral range for all angles of incidence. When using optimization technology, a merit function should be built and must consider the factor of incident angle.

$$MF = \frac{\int_{\lambda_1}^{\lambda_2} \int_{\theta_1}^{\theta_2} S(\lambda)\, SR(\lambda)\, R(\lambda, \theta)\, \mathrm{d}\lambda \mathrm{d}\theta}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, SR(\lambda)\, \mathrm{d}\lambda}, \tag{2}$$

where $S(\lambda)$ is the solar spectrum distribution, $SR(\lambda)$ is the Si material spectrum response, and $R(\lambda, \theta)$ is the reflection of the antireflection with a certain incident angle θ and wavelength λ.

The Si material spectrum response range is 400–1200 nm. Considering solar spectrum distribution, the antireflection should operate at an 800 nm spectral range. In this range, the coating materials have an appreciable dispersion that cannot be neglected and have to be handled properly throughout the whole design process. The high- and low-index materials are TiO_2 and MgF_2. The refractive indices used in the calculation are given in Table 1.

As shown in Table 1, the Si material refractive index is very high. In this situation, a solar cell will have high residual reflection if it has no antireflection, as shown in Fig. 1(a).

To design antireflection, we choose 600 nm as the central wavelength and air|0.3L0.3H0.3LH|Si as the initial stack according to the theory. H and L denote the quarter-wave optical thicknesses of high (TiO_2)- and low (MgF_2)-index materials, respectively. To extend the low-reflectance regime range of the incident angle and wavelength, the conjugate graduate optimization method is used to change the thickness of each layer. We adopt the form of merit function as Eq. (2), in which we choose $\lambda_1 = 400$ nm, $\lambda_2 = 1200$ nm, $\theta_1 = 0°$, and $\theta_2 = 60°$. With respect to the range of the incident angle, we mainly consider that solar light intensity is faint at the rising and setting of the sun. The reflection curve of our design result is shown in Fig. 1(b), and the corresponding optimal parameter is shown in Table 2.

In a general situation, silicon glue was used to encapsulate the solar cell, which can ensure the stability between the solar-cell slice and the parallel plate glass. Its use is also an advantage in the use of solar cells. The refractive index of silicon glue is 1.43. In this condition, the solar cell will still have high residual reflection if it has no antireflection, which is shown in Fig. 2(a). To design antireflection, we adopt glue|0.3H0.3L0.3H0.3LH|Si as the initial stack, and the high- and low-index coating materials are still TiO_2 and MgF_2, respectively. The other parameters are as follows: the central wavelength is 600 nm, λ_1 = 400 nm, λ_2 = 1200 nm, $\theta_1 = 0°$, and θ_2 = 60°. After using the conjugate graduate optimization method, we gain the optimal parameter of each layer, as shown in Table 3. Figure 2(b) shows the corresponding reflectivity versus different incident angles.

In conclusion, the refractive index of Si material is very high, so antireflection coatings are therefore widely utilized to improve the conversion efficiencies of Si solar cells. On the other hand, sun azimuth changes continuously in a cycle of rising to setting. With corresponding spectral responses in Si and the distribution of solar spectra, an ideal antireflection structure should lead to zero reflection loss on solar-cell surfaces over an extended solar spectral range for all angles of incidence. We introduce two multilayer stacks with availability materials (TiO_2 and MgF_2) based on the optical thin-film theory and associate the conjugate graduate optimized technique to change the thickness of each individual layer. When the incident medium is air, we adopt air|0.3L0.3H0.3LH|Si as the initial stack. If the solar cell is encapsulated by silicon glue, the initial stack is glue|0.3H0.3L0.3H0.3LH|Si. The results show that the two designs used in different conditions can evidently reduce the residual reflection.

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