Influence of window layer thickness on double layer antireflection coating for triple junction solar cells*

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Abstract: The optimization of a SiO_2/TiO_2, SiO_2/ZnS double layer antireflection coating (ARC) on $Ga_{0.5}In_{0.5}P/In_{0.02}Ga_{0.98}As$/Ge solar cells for terrestrial application is discussed. The $Al_{0.5}In_{0.5}P$ window layer thickness is also taken into consideration. It is shown that the optimal parameters of double layer ARC vary with the thickness of the window layer.

Key words: reflection curves; optical reflectivity; antireflection; transfer matrix

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1. Introduction

Multi-junction III–V solar cells have embarked on remarkable conversion efficiency. Up to now, the highest efficiency in the world has been achieved by advanced multi-junction solar cells in practice[1]. The cells are of great interest in photovoltaic modules for both terrestrial and space applications, for their good conversion efficiency.

Their established cell structure, including optimal band gap combination and matched tunneling junction, has a fixed ideal maximum efficiency under the same optical absorption. Moreover, the incident light cannot be absorbed completely by solar cells because of the high reflection of the front surface.

To enhance their practical efficiency, the reflection loss should be minimized. Many studies have reported increasing the absorption of solar cells, single layer antireflection coating (ZnO[2], SiN[2] and ZnS[3]), double layer antireflection coating (ARC) (MgF_2/CeO_2[4,5], TiO_2/ZnO[6]), and special structure (silicon nitride on pyramid-texture[7] and porous silicon[8]).

In this paper, a reflection inhibition method to design and optimize a double layer antireflection coating (SiO_2/TiO_2, SiO_2/ZnS) is presented. When the optical thickness of the coating is equal to a quarter of the wavelength, the reflection will be reduced effectively. The effect of ARC particularly depends on the thickness, refractive index of the film, and the wavelength of light[9].

In addition, the thickness of the $Al_{0.5}In_{0.5}P$ window layer was taken into consideration. It is shown that the window layer can influence the reflection as a third layer of the antireflection AR structure[10].

2. Theoretical optimization of SiO_2/TiO_2 and SiO_2/ZnS double AR layers

As it is desirable to have a more efficient device, the optimization of the double AR layers in order to achieve the minimum average reflectivity is crucial. The average reflectivity covers a spectral range and is composed of $R(\lambda)$ defined at a given wavelength.

It is essential to calculate the weighted reflectivity R_w due to the solar spectrum's long range of wavelength from 200 to 2000 nm. The weighted reflectivity[11] can be obtained by integrating the reflectivity $R(\lambda)$, the energy distribution of the solar spectrum $Q(\lambda)$ and internal spectral response of the solar cell $R_{int}(\lambda)$,

$$R_w = \frac{\int_{\lambda_1}^{\lambda_2} R(\lambda) R_{int}(\lambda) Q(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda) Q(\lambda) d\lambda}. \quad (1)$$

In this paper, the solar spectrum of AM1.5 will be taken into account, due to the terrestrial applications of the cells being emphasized. In Eq. (1), 300 nm is taken as the low limit wavelength (λ_1) while 1800 nm is taken as the upper limit wavelength (λ_2) during the computation process because this spectrum range takes a great part of the solar energy. The count of photos $Q(\lambda)$ is decided by the power of every given wavelength.

By the approach of optical admittance, the reflectivity of multilayer films related to wavelength can be calculated. The process will be described in the next paragraph.

A ray incident vertically on the surface of the film structure is considered (see Fig. 1). The structure contains j layers that each has thickness d_k, and refractive index n_k, and it also contains a substrate whose refractive index is n_s. Moreover, the air refractive index is taken as 1.

The reflectivity of the whole system can be calculated from

$$R(\lambda) = \left| \frac{E_0 - H_0}{E_0 + H_0} \right|^2, \quad (2)$$

where E_0 is the electric amplitude and H_0 is the magnetic amplitude of the electromagnetic wave at the interface between

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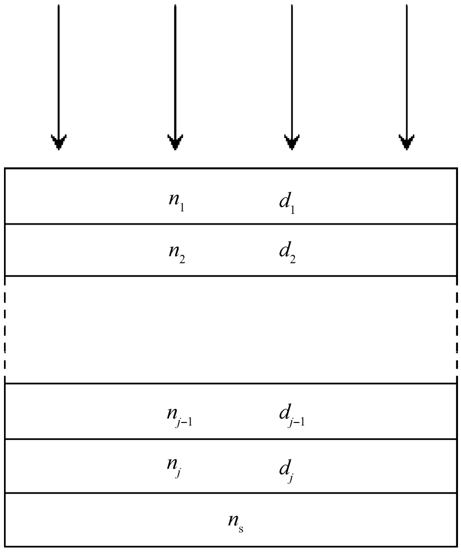


Fig. 1. A ray incident on a thin film system where each layer has thickness d_k and refractive index n_k.

the air and first layer. The two parameters should be calculated in order to get the reflectivity of the whole multilayer system.

The numeration of E_0 and H_0 are shown by the transfer matrix[12] (see Eqs. (3) and (4)),

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = \prod_{k=1}^{j} \begin{pmatrix} \cos\delta_k & i\sin\delta_k/n_k \\ i n_k \sin\delta_k & \cos\delta_k \end{pmatrix} \begin{pmatrix} 1 \\ n_s \end{pmatrix} E_{j+1}, \quad (3)$$

$$\delta_k = \frac{2\pi n_k d_k}{\lambda}. \quad (4)$$

The internal spectral response of a solar cell $R_{\rm int}(\lambda)$ is also one factor of $R_{\rm w}$, but our procedure neglects its influence, because $R_{\rm int}(\lambda)$ of each cell has no evident difference. Supposing $R_{\rm int}(\lambda)$ of each cell is the same, $R_{\rm w}$ can be reduced to its simplest form (see Eq. (5)), which is defined as the average effective reflectivity $R_{\rm e}$,

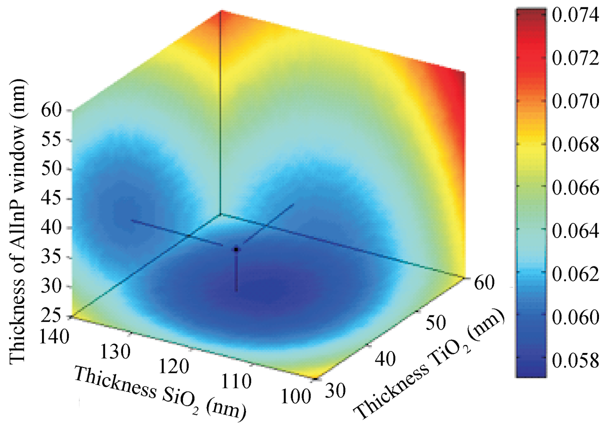
$$R_{\rm e} = \frac{\int_{\lambda_1}^{\lambda_2} R(\lambda)Q(\lambda)\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} R(\lambda)Q(\lambda)\mathrm{d}\lambda}. \quad (5)$$

When it comes to SiO_2/TiO_2 and SiO_2/ZnS double ARC on triple junction solar cells, the $Al_{0.5}In_{0.5}P$ window layer should be treated as a third layer of the system. The minimum average effective reflectivity is realized by the proper layer thickness of three films in this simulation.

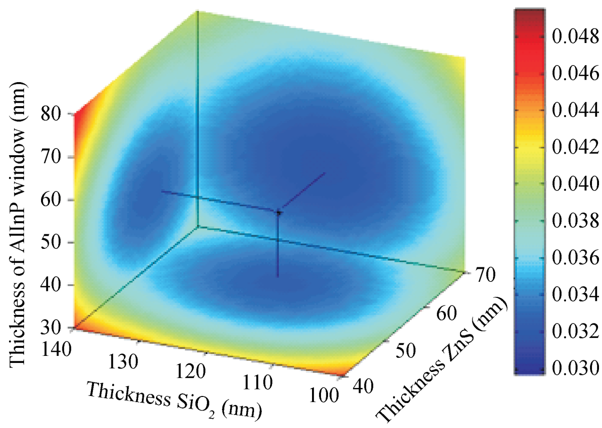
3. Simulations and results

In this paper, the SiO_2/TiO_2 and SiO_2/ZnS double ARC are well simulated. The refractive indexes of SiO_2, TiO_2, ZnS and $Al_{0.5}In_{0.5}P$ are collected by various ways. The results will be influenced slightly, since the values of refractive indices are usually measured in bulk crystal. The detailed procedure, analysis, and comparison are provided in the next paragraph.

Through the simulation program, the average effective reflectivity of SiO_2/TiO_2 and SiO_2/ZnS double ARC are calculated. The results are shown in a four dimensional figure



(a)



(b)

Fig. 2. These four dimensional figures show the optimal simulated results of (a) SiO_2/TiO_2 and (b) SiO_2/ZnS double AR under AM1.5 conditions.

(see Fig. 2). In Fig. 2(b), the optimization of a SiO_2/TiO_2 double ARC (TiO_2: 40 nm, SiO_2: 120 nm, $Al_{0.5}In_{0.5}P$: 30 nm) gains $R_{\rm e}$ of 5.71%. Note that, in Fig. 2(a), $R_{\rm e}$ of the optimal SiO_2/ZnS double ARC (ZnS: 60 nm, SiO_2: 120 nm, $Al_{0.5}In_{0.5}P$: 40 nm) is reduced to 2.97%. In contrast to the SiO_2/TiO_2 ARC, the SiO_2/ZnS ARC achieves better performance.

To make a further comparison between the two structures, we analyze the reflectivity of each wavelength of solar spectrum AM1.5 under the optimal condition in Fig. 3. From 300 to 1800 nm, the reflectivity of SiO_2/ZnS ARC is lower than SiO_2/TiO_2 ARC. In particular, the reflectivity of SiO_2/TiO_2 ARC in 600–800 nm is almost zero, while the SiO_2/ZnS ARC extending from 600 nm to near infrared band 1200 nm is without reflection. This indicates that solar cells with SiO_2/ZnS ARC can make better use of the energy of the near infrared band and achieve higher efficiency.

With all of the above simulation results, the optimal thickness of the window layer is clear. However, the control of thickness is not accurate enough. The average effective reflectivity is analyzed when the thickness of the window layer is changed from 0 to 75 nm (see Fig. 4). Whatever the changes are, thicker or thinner, the average effective reflectivity is in-

Table 1. Variation in average effective reflectivity is shown by simulation when the window layer thickness deviates from the optimal value.

$SiO_2/TiO_2/Al_{0.5}In_{0.5}P$		$SiO_2/ZnS/Al_{0.5}In_{0.5}P$	
Variation in window layer thickness (nm)	Variation in effective reflectivity (%)	Variation in window layer thickness (nm)	Variation in effective reflectivity (%)
20	5.82	30	3.12
25	5.73	35	3.02
35	5.74	45	2.98
40	5.82	50	3.03

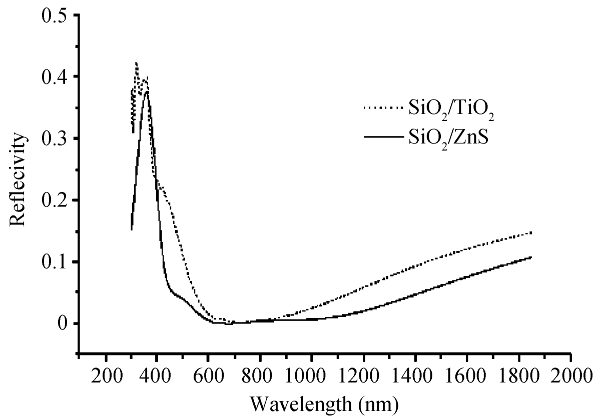


Fig. 3. Comparison of reflectivity of SiO_2/TiO_2 and SiO_2/ZnS double ARC of optimal value under AM1.5.

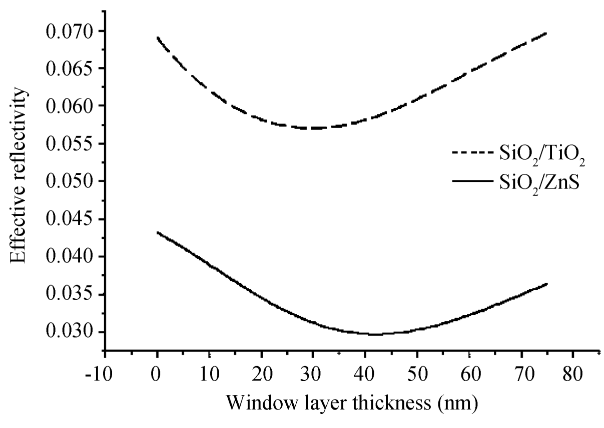


Fig. 4. Effective reflectivity with different window layer thickness

creased. Table 1 shows that the average effective reflectivity of SiO_2/ZnS ARC is more sensitive than SiO_2/TiO_2 ARC when the window layer thickness changes. The tendency of increasing average effective reflectivity of SiO_2/ZnS ARC is changeless when the window layer thickness varies. For the SiO_2/ZnS ARC, the average effective reflectivity increases more rapidly when the window layer is thinner. This means that it will not introduce a sharp increase in R_e when the window layer thickness is a little greater.

The reflectivity in logarithmic coordinates at different window layer thicknesses versus wavelength is further discussed (see Fig. 5). In Fig. 5(a), the curves of SiO_2/TiO_2 ARC are calculated at different window layer thicknesses (5, 35, and 65

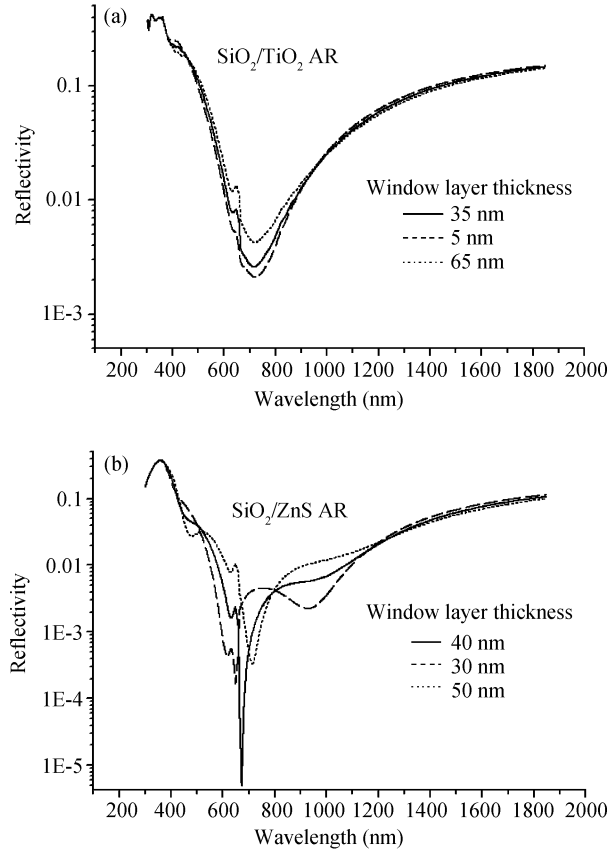


Fig. 5. Reflectivity curve of different window layer thicknesses due to the solar spectrum AM1.5 in the log coordinate.

nm). The minimum reflectivity point keeps almost at the same wavelength when the window layer is changed. In Fig. 5(b), the curves of SiO_2/ZnS ARC are given at different window layer thicknesses (30, 40, and 50 nm). The curves of Fig. 5(b) are marked different from Fig. 5(a). The minimum reflectivity point evidently moves to a longer wavelength when the window layer is thicker, while the minimum point position evidently moves to a shorter wavelength when the window layer is thinner. This means that we can judge a variety of window layers, thicker or thinner, by this characteristic.

4. Conclusion

Theoretical computation of the SiO_2/TiO_2, SiO_2/ZnS double layer antireflection coating (ARC) on the $Al_{0.5}In_{0.5}P$ window layer shows that this structure can achieve a highly effective reflectivity of 5.71% and 2.97%, respectively. In contrast with SiO_2/TiO_2 AR, SiO_2/ZnS, AR can achieve a better antireflective effect because the minimum reflectivity of SiO_2/ZnS AR expands to the near infrared band. Calculation based on changing the window layer thickness shows that the effective reflectivity of SiO_2/ZnS AR is more sensitive to the window layer thickness than SiO_2/TiO_2 AR. It notes that a thicker SiO_2/ZnS AR structure will not introduce more reflective losses.

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