# An effective reflectance method for designing broadband antireflection films coupled with solar cells*

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The solar spectrum covers a broad wavelength range, which requires that antireflection coating (ARC) is effective over a relatively wide wavelength range for more incident light coming into the cell. In this paper, we present two methods to measure the composite reflection of $SiO_2$/ZnS double-layer ARC in the wavelength ranges of 300–870 nm (dual-junction) and 300–1850 nm (triple-junction), under the solar spectrum AM0. In order to give sufficient consideration to the ARC coupled with the window layer and the dispersion effect of the refractive index of each layer, we use multi-dimensional matrix data for reliable simulation. A comparison between the results obtained from the weighted-average reflectance (WAR) method commonly used and that from the effective-average reflectance (EAR) method introduced here shows that the optimized ARC through minimizing the effective-average reflectance is convenient and available.

**Keywords:** weighted-average reflectance, effective-average reflectance, transfer matrix

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## 1. Introduction

The fabrication of a high-efficiency solar cell (SC) requires the reduction of the incident photon flux loss on the SC surface. For this purpose, many types of antireflection (AR) structures for different SCs have been investigated.[1−7] As for III-V tandem SCs, an appropriate combination of transparent thin films is stacked on the SC surface, forming an antireflection coating (ARC).[8] As a result, the number of incident photons transmitting to the SC active areas is maximized, thereby increasing the short-circuit current ($J_{sc}$). The SCs operate in a broad spectrum, which means that a broadband ARC is necessary.

There are many types of broadband ARC. Flat multiple-layer ARC, such as double-, triple-, and quadruple-layer ARCs, are all used. It has been demonstrated that a single layer of coating is not effective enough because it only reduces reflectance in a narrow spectral range. A further decrease of reflectance may be achieved using a double- or even a triple-layer ARC.[9−12] In view of the uncomplicated fabrication process and low cost, we always use a double-layer ARC. In this paper, we introduce the principle and method of AR films, and then use a multi-dimensional matrix for the refractive index dispersion effect of each layer to simulate the reflectance of the multi-optical-film system. Furthermore, we introduce a simplified effective-average reflectance (EAR) method to design the ARC. A comparison between the results of dual- and triple-junction SCs with that obtained from the weighted-average reflectance (WAR) method commonly used proves that the ARC optimized through the EAR method is more convenient and available under the AM0 conditions. This paper is organized as follows. In Section 2 we present the models to optimize the multi-layer ARC. The differences between the results obtained by the models in Section 2 and that obtained by a typical double-layer ARC are discussed in Section 3. Finally the conclusion is provided in Section 4.

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## 2. Model and method

The transfer matrix method has been used to model the reflectance of the system, as this approach can be applied to analyse multi-layer films with different values of thickness, refractive index ($n$) and extinction coefficient ($k$) on a substrate. In general, we model the reflectance at normal incidence of a double-layer $SiO_2$/ZnS AR coating in $Al_{0.5}In_{0.5}P$ window layer in front of a $Ga_{0.5}In_{0.5}P$ top cell. The program lies in previously measured optical parameters for materials such as $Al_{0.5}In_{0.5}P$, $Ga_{0.5}In_{0.5}P$,[13] as well as some other materials[12−15] used as AR coatings. Figure 1 indicates the optical constants of the ARC and $Al_{0.5}In_{0.5}P$ window layer materials which mainly determine the reflectance of the film system. We did not consider the extinction coefficient of $SiO_2$ here due to its transparency in the wave bands of interest. The optical parameters of any composition of AR coating were determined by cubic interpolation.

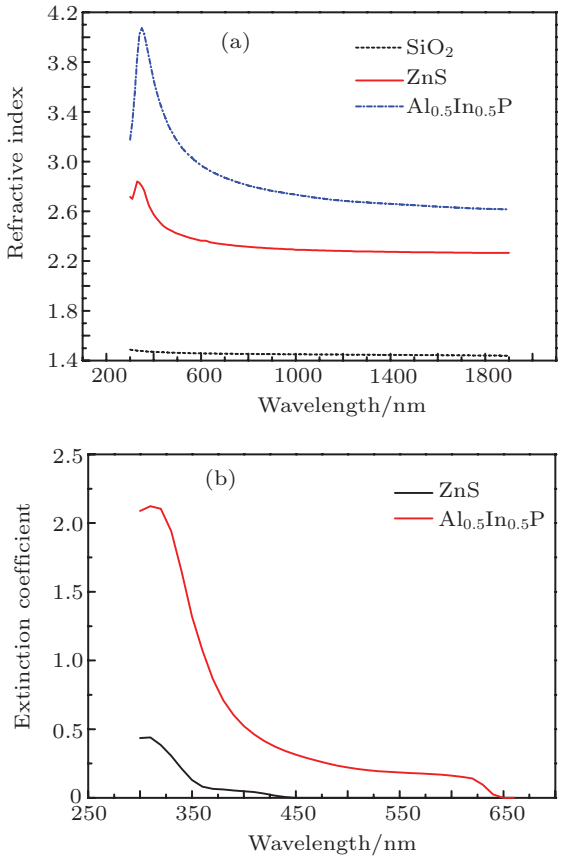



**Fig. 1.** (colour online) Optical constants of key films as functions of the wavelength. (a) Refractive index, (b) extinction coefficients.

Specifically speaking, the method used for calculating the reflectance ($R$) of the stacked film includes a matrix expression of the boundary conditions on the film surfaces, derived from the Maxwell equations.[16,17] It can be used for the obliquely incident polarized light. Usually, considering a simpler normal incident case is effective enough.

The complex refractive index is defined as $n - \mathrm{i}\,k$ (see Fig. 2), where $n$ is the real part of the index of refraction and $k$ is the extinction coefficient, which is related to the absorption coefficient $\alpha$ by $k = \alpha\lambda/4\pi$ with $\lambda$ being the wavelength. The incident medium has the real refractive index $n_0$, the complex refractive index of the substrate is $n_s$, and $T$ the transmittance of the stacked film. We consider the case of air ($n_0 = 1$) here. When monochromatic light enters the films at normal incidence, each film is represented independently by its characteristic matrix $\boldsymbol{M}_J$, which is defined as

$$\boldsymbol{M}_J = \begin{bmatrix} \cos\delta_j & \mathrm{i}\sin\delta_j/n_j \\ \mathrm{i}\,n_j\sin\delta_j & \cos\delta_j \end{bmatrix} \tag{1}$$

with

$$\delta_j = \frac{2\pi n_j d_j}{\lambda}, \tag{2}$$

where $\delta_j$ is called the effective optical thickness of the layer at a wavelength, $2\delta_j$ is equal to the phase difference between two adjacent coherent light beams. A characteristic matrix formulation of the film system is obtained by multiplying $\boldsymbol{M}_J$ as

$$\begin{aligned} \begin{bmatrix} B \\ C \end{bmatrix} &= \left\{ \prod_{j=1}^{N} \begin{bmatrix} \cos\delta_j & \mathrm{i}\sin\delta_j/n_j \\ \mathrm{i}\,n_j\sin\delta_j & \cos\delta_j \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \\ &= \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix}, \end{aligned} \tag{3}$$

where $Y = C/B$ is the optical admittance. The reflectance $R$ of the whole film system is given by

$$R = |r|^2 = \left| \frac{n_0 - Y}{n_0 + Y} \right|^2. \tag{4}$$

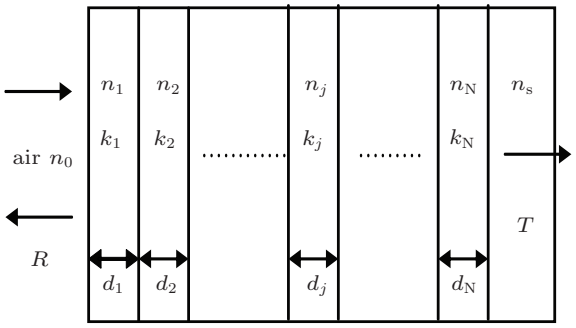



**Fig. 2.** Sketch of the optical model for stacked film.

The solar spectrum covers a broad wavelength range, which requires the solar cells to have relatively low reflectance in a wavelength range as wide as possible. To estimate the reflection in a wide wavelength range, we should find an average-weighted reflectance[18]

$$R_{\rm w} = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda)R(\lambda)Q(\lambda)\,{\rm d}\lambda}{\int_{\lambda_1}^{\lambda_2} F(\lambda)Q(\lambda)\,{\rm d}\lambda}, \tag{5}$$

where $F(\lambda)$ is the incident photon flux,[19] $Q(\lambda)$ is the internal quantum efficiency (IQE) of the solar cell,[20−22] $R(\lambda)$ is the reflectance of the monochromatic light, $\lambda_1$ represents the lower limit of spectral response, and $\lambda_2$ for the upper limit.

In practical applications, there is only a small difference in IQE between sub cells in the absorbed wavelength range. The assumption that IQEs are equal will not influence the reliability of results much, so the effective average reflectance $R_{\rm e}$ for convenient design is given by[23]

$$R_{\rm e} = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda)R(\lambda)\,{\rm d}\lambda}{\int_{\lambda_1}^{\lambda_2} F(\lambda)\,{\rm d}\lambda}. \tag{6}$$

## 3. Results and discussion

In this section, we present the results of the weighted average reflectance and effective average reflectance for the $SiO_2$/ZnS double-layer structure on dual- and triple-junction solar cells under the AM0 conditions.

### 3.1. $Ga_{0.5}In_{0.5}P$/GaAs dual-junction solar cell (300–870 nm)

Figures 3 and 4 show the optimal parameters of $SiO_2$/ZnS ARC for $Ga_{0.5}In_{0.5}P$/GaAs dual junction solar cell under the AM0 conditions. The curves of $SiO_2$/ZnS film reflectance optimized by EAR and WAR methods are shown in Fig. 5. Parameters of $SiO_2$/ZnS ARC for dual junction SC optimized by different methods are summarized in Table 1.

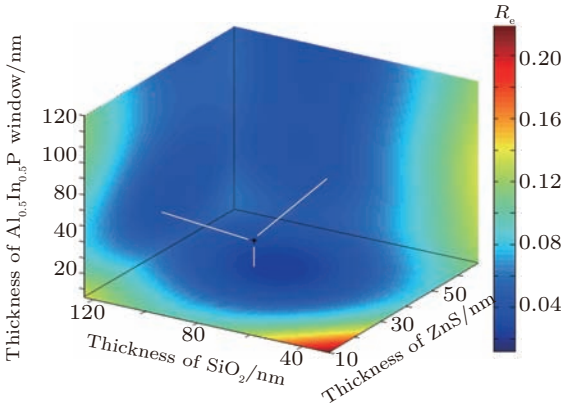



**Fig. 3.** (colour online) $R_{\rm e}$ of $SiO_2$/ZnS ARC versus film thickness.

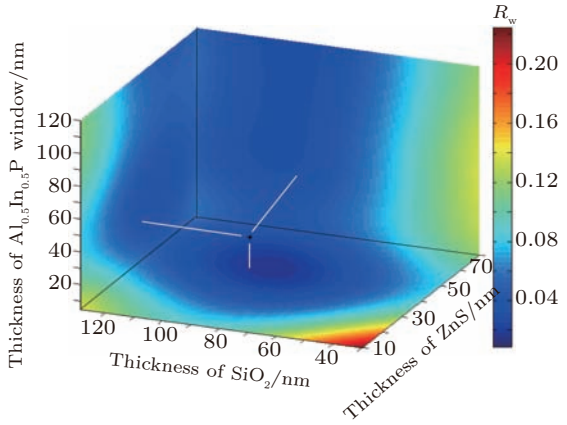



**Fig. 4.** (colour online) $R_{\rm w}$ of $SiO_2$/ZnS ARC versus film thickness.

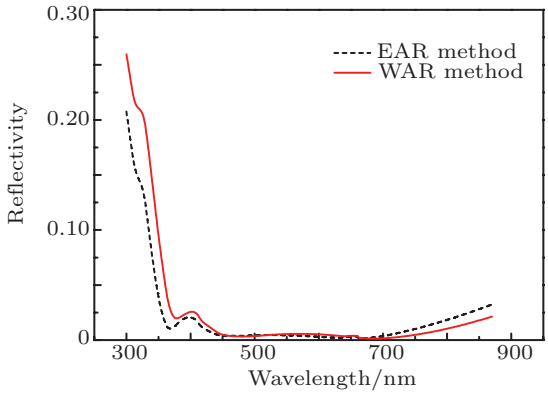



**Fig. 5.** (colour online) Optimized $SiO_2$/ZnS ARC reflectance versus wavelength.

**Table 1.** Comparison of parameters of $SiO_2$/ZnS ARC for dual-junction SC optimized by different methods.

| | $SiO_2$ thickness/nm | ZnS thickness/nm | Window layer thickness/nm | Average reflectance ($R_{\rm e}/R_{\rm w}$) |
|---|---|---|---|---|
| Optimized by EAR method | 85 | 37 | 29 | 1.21% |
| Optimized by WAR method | 90 | 40 | 30 | 0.87% |
| Change | –5.6% | –7.5% | –3.3% | 0.34% |

For the dual-junction SC, the parameters of $SiO_2$/ZnS ARC optimized by EAR and WAR methods have a slight difference (see Table 1): the difference in thickness is less than 5 nm, and the reflectances are almost the same in a 400–700 nm spectral range, where the solar photon flux is mainly dispersive (see Fig. 5) and the ARC is effective. The results indicate that optimizing an ARC by using the EAR method for the dual junction SC is available.

### 3.2. $Ga_{0.5}In_{0.5}P$/GaAs/Ge triple junction solar cell (300 nm–1850 nm)

Figures 6 and 7 show the optimal parameters of $SiO_2$/ZnS ARC for a $Ga_{0.5}In_{0.5}P$/GaAs/Ge triple junction solar cell under the AM0 conditions. The curves of $SiO_2$/ZnS film reflectance optimized by EAR and WAR methods are shown in Fig. 8. Parameters of $SiO_2$/ZnS ARC for the triple-junction SC optimized by different methods are summarized in Table 2.

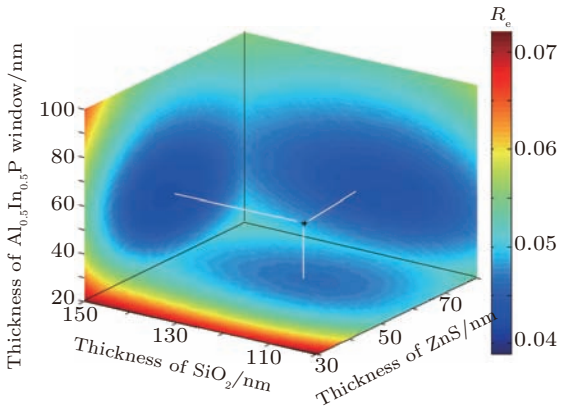



**Fig. 6.** (colour online) $R_e$ of $SiO_2$/ZnS ARC versus film thickness.

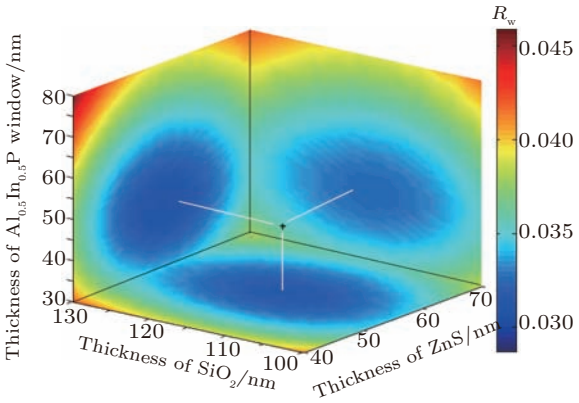



**Fig. 7.** (colour online) $R_w$ of $SiO_2$/ZnS ARC versus film thickness.

**Table 2.** Comparison of parameters of $SiO_2$/ZnS ARC for a triple-junction SC optimized by using different methods.

| | $SiO_2$ thickness/nm | ZnS thickness/nm | Window layer thickness/nm | Average reflectance ($R_e$/$R_w$) |
|---|---|---|---|---|
| Optimized by EAR method | 122 | 58 | 47 | 3.89% |
| Optimized by WAR method | 115 | 56 | 46 | 2.87% |
| Change | –6.1% | –3.6% | –2.2% | 1.02% |

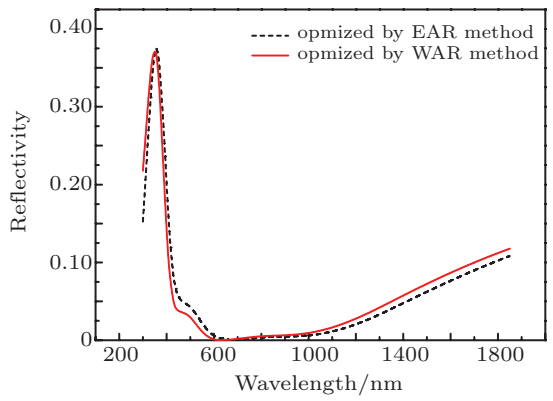



**Fig. 8.** (colour online) Optimal $SiO_2$/ZnS ARC Reflectance versus wavelength.

For the triple-junction SC, the parameters of the $SiO_2$/ZnS ARC optimized by using the EAR and WAR methods also have a slight difference (see Table 2): the difference in thickness is less than 10 nm, which is still acceptable. The reflectances are almost the same in a 400–700 nm band, where the solar photon flux is mainly dispersive (see Fig. 8) and the ARC is effective. The results indicate that optimizing the ARC by using the EAR method for triple-junction SCs is available.

## 4. Conclusion

Theoretical optimization of a $SiO_2$/ZnS double layer ARC in the $Al_{0.5}In_{0.5}P$ window layer for dual- and triple-junction solar cells under the solar radiation AM0 shows that the final optimal ARC parameters obtained by using the WAR and EAR methods change slightly comparatively. Specifically, for the dual junction SC, the ARC thickness is changed by less than 5 nm, the average reflectance is changed by 0.34%. For the triple junction SC, the ARC thickness is changed by less than 10 nm, the average reflectance

is changed by 1.02%. The slight change of parameters is acceptable. In addition, optimizing the ARC through the introduced EAR method instead of the WAR method commonly used is applicable.

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