Research Article

Design Multilayer Antireflection Coatings for Terrestrial Solar Cells

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Received 31 August 2013; Accepted 19 November 2013; Published 28 January 2014

Academic Editors: E. Liu, A. Meghea, H. Ruda, and Z. Yang

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In order to analyze the influence of methods to design antireflection coatings (ARCs) on reflectivity of broadband solar cells, we provide detailed analyses about the ARC coupled with a window layer and the refractive index dispersion effect of each layer. By multidimensional matrix data simulation, two methods were employed to measure the composite reflection of a SiO₂/ZnS double-layer ARC within the spectral ranges of 300–870 nm (dual junction) and 300–1850 nm (triple junction) under AM1.5 solar radiation. A comparison study, between the results obtained from the commonly used weighted average reflectance method (WAR) and that from the introduced effective average reflectance method (EAR), shows that the optimization of ARC by EAR method is convenient and feasible.

1. Introduction

Reflective loss of the incident light on the device surface is an important factor that affects efficiency of solar cell (SC). Design of antireflection structure has become a key factor in SC fabrication [1–7]. For III–V tandem SCs, a proper group of transparent materials are deposited on the SC surface, leading to the formation of antireflection coatings (ARCs) [7, 8]. Consequently, the reflective loss of the incident lights would be minimized and the SCs work in a spectral range with higher efficiency. Therefore, broadband ARCs are essential for SCs operating at a broad spectrum.

Generally, there are various types of broadband ARC. For instance, flat multilayer ARCs can be double, triple, or quadruple layer. Many studies have shown that the performance of a single layer coating is not satisfying due to its narrow working spectral range. Double-, triple-, or even multiple-layer ARCs [7, 9–11] have better performance when referring to broadband SCs. Double-layer ARCs are commonly used because of their simple fabrication process and low cost. In this paper, the principle and method of antireflective films were introduced. A multidimensional matrix for the refractive index dispersion effect of each

layer was used to simulate the reflectivity of several optical film systems. An effective average reflectance R_e method (EAR) simplified from the commonly used weighted average reflectance R_w method (WAR) was also utilized to design ARCs. The optimizations of ARCs in the dual- and triple-junction SCs by two methods were compared and analyzed. Accordingly, it demonstrates that optimizing ARC by minimizing R_e is more convenient under the AM1.5 conditions. The models for optimization of multilayer ARC are presented in the following section, and their differences from a typical double-layer ARC are discussed in detail thereafter.

2. Methodology

The reflectivity at normal incidence of a SiO₂/ZnS double-layer antireflection coating (ARC) on an Al_{0.5}In_{0.5}P window layer is typically modeled in front of a Ga_{0.5}In_{0.5}P top cell. This approach is based on previously measured optical parameters for materials such as Al_{0.5}In_{0.5}P and Ga_{0.5}In_{0.5}P [12], as well as others [12–14] used as ARCs. The optical parameters of any composition of ARC are generally determined by cubic interpolation. We adopted the transfer-matrix method to model the reflectance of the system, as this

FIGURE 1: Schematic diagram of the optical model for stacked films.

approach can be used to analyze multilayer films of varying thickness, refractive indices (n), and extinction coefficients (k) on a substrate.

Optical interference matrix is an effective way to calculate reflectivity of film. To allow the situation that the incident angle of light is zero degree, considering the optical thin film system of N layers prepared on the substrate as shown in Figure 1, n_j is the refractive index and k_j is the extinction coefficient, d_j is the thickness in each layer, respectively, and n_0 is refractive index of air ($n_0 = 1$). According to the refractive index and thickness of each layer, interference matrix of each layer can be determined. A characteristic matrix formulation of the film system is obtained by multiplying interference matrix of each layer [15]:

$$\begin{aligned} \begin{bmatrix} B \\ C \end{bmatrix} &= \left\{ \prod_{j=1}^N \begin{bmatrix} \cos \delta_j & \frac{i \sin \delta_j}{n_j} \\ i n_j \sin \delta_j & \cos \delta_j \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \\ &= \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix}, \end{aligned} \quad (1)$$

where δ_j is the effective optical thickness of the layer at a given wavelength. The $2\delta_j$ is equal to the phase difference of two adjacent coherent light beams. $Y = C/B$ is the optical admittance. The reflectivity R of the whole film system is expressed as

$$R = |r|^2 = \left| \frac{n_0 - Y}{n_0 + Y} \right|^2. \quad (2)$$

The solar spectrum spans a broad range of wavelengths. To enable more incident light to enter the SC, the internal quantum efficiency of the material and the sun's spectral characteristics should all be considered during the design of ARCs. The weighted average reflectivity within the entire spectrum can be calculated by the incident photon flux $F(\lambda)$ [16], the internal quantum efficiency (IQE) of the SC $Q(\lambda)$ [17, 18], and the reflectivity of monochromatic light $R(\lambda)$ [19]:

$$R_w = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) R(\lambda) Q(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} F(\lambda) Q(\lambda) d\lambda}, \quad (3)$$

FIGURE 2: SiO₂/ZnS ARC R_e versus films thickness.

where λ_1 represents the lower limit of spectral response and λ_2 represents the upper limit.

Considering that there are minor differences in IQEs among different monochromatic light in practical applications, we set IQEs equal to induce the average effective reflectance R_e for a convenient design [20]:

$$R_e = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) R(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} F(\lambda) d\lambda}. \quad (4)$$

3. Results and Discussion

In this section, we will discuss the minimization results obtained for the weighted average reflectance and effective average reflectance of the SiO₂/ZnS double-layer structure on double- and triple-junction SCs under AM1.5 conditions.

3.1. Dual Junction Solar Cell (300–870 nm). The four-dimensional images shown in Figures 2 and 3 depict the optimal parameters of the SiO₂/ZnS ARC for the Ga_{0.5}In_{0.5}P/GaAs double-junction SC under AM1.5 conditions. The reflectivity curves of SiO₂/ZnS films optimized by R_e and R_w are shown in Figure 4. The SiO₂/ZnS ARC parameters for the double-junction SC optimized by different methods are summarized in Table 1.

Those optimized by R_e and R_w exhibited minimal differences (see in Table 1), with the change in thickness values being less than 2 nm and the reflectivities in the spectral range of 400–700 nm remaining almost unchanged, that these reflectivities are the lowest where the solar photon flux is mainly distributed (see Figure 4). These results indicated that optimizing the ARC by minimizing the effective average reflectance R_e for double-junction SC is feasible.

3.2. Triple Junction Solar Cell (300–1850 nm). The four-dimensional images shown in Figures 5 and 6 depict

TABLE 1: Comparison of parameters of SiO_2/ZnS ARC for dual junction SC optimized by different methods.

	Optimized by EAR method	Optimized by WAR method	Change
SiO_2 thickness (nm)	94	95	-1.05%
ZnS thickness (nm)	42	43	-2.32%
Window layer thickness (nm)	31	31	0%
Average reflectance (R_e/R_w)	0.75%	0.68%	0.07%

FIGURE 3: SiO_2/ZnS ARC R_w versus films thickness. FIGURE 5: SiO_2/ZnS ARC R_e versus films thickness. FIGURE 4: Optimal SiO_2/ZnS ARC reflectivity versus wavelength. FIGURE 6: SiO_2/ZnS ARC R_w versus films thickness.

the optimal parameters of the SiO_2/ZnS ARC for the $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}/\text{Ge}$ triple-junction SC under AM1.5 conditions. The reflectivity curves of SiO_2/ZnS films optimized by R_e and R_w are shown in Figure 7. The SiO_2/ZnS ARC parameters for the triple-junction SC optimized by different methods are summarized in Table 2.

Those optimized by WAR and EAR methods also exhibited minimal differences in triple junction SC (see in Table 2), with the change in thickness values being less than 2 nm and the reflectivities in the spectral range of 400–700 nm remaining almost unchanged. The reflectivities are properly the lowest where the solar photon flux is mainly distributed (see Figure 7). These results indicated that optimizing the ARC by minimizing the effective average reflectance R_e for double-junction SC is feasible.

TABLE 2: Comparison of parameters of SiO₂/ZnS ARC for triple junction SC optimized by different methods.

	Optimized by EAR method	Optimized by WAR method	Change
SiO ₂ thickness (nm)	121	116	4.31%
ZnS thickness (nm)	59	56	5.36%
Window layer thickness (nm)	47	44	6.82%
Average reflectance (R_e/R_w)	2.97%	2.21%	0.76%

FIGURE 7: Optimal SiO₂/ZnS ARC reflectivity versus wavelength.

4. Summary

To summarize, this study represents the theoretical optimization of the SiO₂/ZnS double-layer ARC on the Al_{0.5}In_{0.5}P window layer for double- and triple-junction SCs under AM1.5 condition. It demonstrated that there are no considerable differences in the final optimal ARC parameters by WAR method and EAR method. For the double-junction SC, the changes in ARC thickness and average reflectivity were determined to be less than 2 nm and 0.07%, respectively. On the other hand, for the triple-junction SC, the corresponding values obtained were less than 6 nm and 0.76%, respectively. These slight changes in the parameters are acceptable. Therefore, optimizing ARCs by minimizing the R_e introduced, instead of R_w , as is commonly used, is thus a viable technique under AM1.5 condition.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work has been sponsored by the Scientific Research Foundation of Guangxi University (Gant no. XBZ120145), the Natural Science Foundation of Guangxi of China (Grant no.

2013GXNSFBA019019), the Key Project of Guangxi Science and Technology Lab Center (Gant no. LGZX201105), the National Natural Science Foundation of China (Grant no. 11364003), and the Open Fund of Ministry-province jointly-constructed Cultivation Base for State Key Laboratory of Processing for Non-ferrous Metal and Featured Materials, Guangxi Zhuang Autonomous Region (Gant no. GXKFJ12-01).

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