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Optimization of multilayer antireflection coating for photovoltaic applications

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ABSTRACT

Multilayer antireflection coating (ARC) for photovoltaics is optimized using Differential Evolution (DE) algorithm. A general transfer-matrix based mathematical formulation is used for evaluating reflection spectra of the system. Exact and complete values of refractive indices are used in the analysis to provide higher accuracy of the results. The proposed optimization method takes into account the solar irradiance spectra, absorption characteristics of semiconductors and angle of incidence to maximize efficiency. This method is found to reduce the average reflectance for a wide range of angles of incidence. The proposed method is used to design ARC for silicon solar cell and a multi-junction AlGaAs/GaAs/Ge solar cell. Finally, comparative analysis of different ARC designs is provided in terms of corresponding solar cell characteristics.

1. Introduction

Antireflection coatings (ARCs) are widely used on the surface of various optical devices to reduce light reflection and improve performance. Silicon cells are the commercially predominant photovoltaic technology because of their ease of fabrication and low manufacturing costs. However, the reflectivity of bare silicon surface can exceed 30% [1], which significantly limits the efficiency of silicon photovoltaics. Multi-junction solar cells like AlGaAs/GaAs/Ge cells also have high reflectivity from their top surfaces. Hence, reflection reduction techniques such as ARC [2], textured front surface design [3] and black silicon surfaces [4] have been implemented to improve solar cell efficiency. Plasmonic structures employing metal nano-particles to enhance light absorption have also been used for this purpose [5]. Each of these methods has its own comparative advantages and disadvantages. This paper concentrates on reflectance reduction utilizing multilayer ARC structure.

ARCs take advantage of phase change of light as it passes through and reflects from media of different refractive indices and thicknesses. By properly selecting the material and thickness of each layer, reflected light of a range of wavelengths can be made to interfere destructively, making the reflectance low. A schematic representation of ARC for silicon photovoltaics is shown in Fig. 1. ARCs are fabricated by depositing very thin films of dielectric materials on the top surface of the photovoltaic devices. These depositions can be performed by thermal evaporation, reactive sputtering, plasma enhanced chemical vapor deposition, sol-gel methods, etc. [6]. These methods are well developed and relatively inexpensive, making ARC an attractive choice. Usually, a single ARC layer is effective for a narrow band of wavelengths [1]. However, the active band of typical silicon solar cells or multi-junction solar cells can be much larger (around 400–1000 nm). Thus, multilayer ARCs are usually used. Commonly used materials for ARCs are TiO_2, SiO_2, Si_3N_4, Al_2O_3, ZnO, etc. [6,7]. TiO_2 is one of the most popular materials for ARC design due to its high refractive index and the transparent band center coinciding with the visible spectrum of sunlight [1]. Si_3N_4 is another popular material due to its stability and good insulating property. Using these materials along with a low index material such as SiO_2, very high performance ARCs can be designed [6,8]. The results presented in this paper are based on ARC designs with TiO_2, SiO_2 and Si_3N_4 materials for silicon cells as well as for AlGaAs/GaAs/Ge cells. However, the analysis is general and can be applied to ARC designs of any material.

The amount of light reflected from a solar cell with ARC depends on the refractive indices and thicknesses of the different layers, the angle of incidence, wavelength of light, and polarization of light. The objective is to select appropriate materials for each layer and optimum thicknesses of those layers. However, taking into account the wavelength dependence of refractive index, the relationship between reflectance and layer thickness is not obvious. Moreover, as the number of layer increases, the equations become too complicated to give an intuitive answer.

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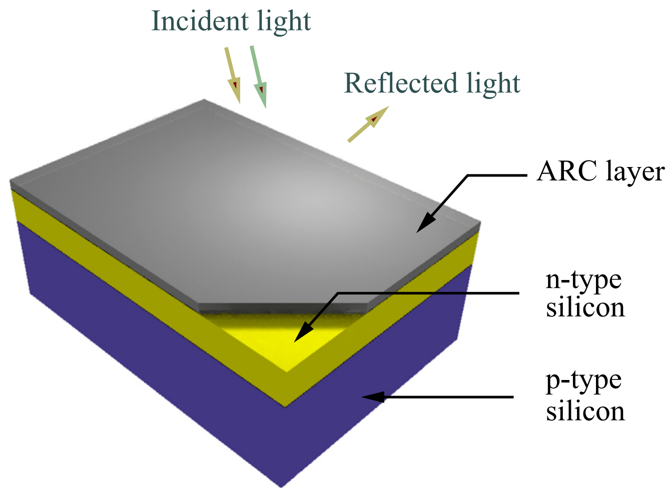

Fig. 1. Schematic representation of ARC layer on silicon photovoltaic.

So, optimization methods are required to design efficient ARCs [9,10]. Stochastic optimization algorithms such as Genetic Algorithm (GA) and Immune Algorithm (IA) can be useful tools for designing ARCs [8,11]. Use of such stochastic evolutionary algorithms can generate a robust optimum solution for any arbitrary reflectance profile requirement [12]. This paper utilizes Differential Evolution (DE) algorithm [13], which is a powerful stochastic optimizer that usually has a faster convergence rate than GA [14].

Although several methods of ARC optimization have been reported in the literature, this work contains some key contributions. Some of the previous works neglect the wavelength dependence of the refractive indices of the materials [6,15]. Thus, those analyses are not exact for the entire band of wavelengths the solar cell operates under. Also, solar spectral irradiance is not considered for the optimization procedure in many cases. The work presented in [16] takes into account the solar spectra and wavelength dependence of refractive index, but ignores the reflectance variation with the incidence angle. However, there has been experimental work taking into account these three factors [17]. The work presented in this paper takes into account all of the aforementioned factors into consideration and presents an exact general theoretical and numerical analysis. Due to the general formulation, the analysis is applicable for arbitrary number of layers in ARC structure. Since the presented analysis takes into account the complex refractive indices of the media, the analysis can yield accurate results for the small wavelength regime where dielectric materials can be lossy and can have non-zero extinction coefficients. Other lossy structures such as metal-dielectric coatings can also be analyzed using this method [18]. This work also takes into account the solar energy absorption characteristics of the photovoltaic cell along with solar spectral irradiance during optimization. Thus, the optimized ARC is tuned to work specially well for the wavelengths where both solar radiation and the semiconductor absorption are high. Also, the application of DE algorithm ensures thorough exploration of the solution space and fast convergence to global optima. The paper uses the proposed method to design ARCs for a silicon cell as well as for a multi-junction AlGaAs/GaAs/Ge solar cell. For the silicon cell, the performance of the ARC is compared with the performance of a black silicon solar cell [19].

The paper is organized as follows: Section 2 contains the mathematical analysis of optical reflection and transmission phenomena through the ARC; Section 3 describes the design, fitness function definition and optimization procedure; Section 4 presents results of optimized reflectance characteristics and comparative performance analysis of the photovoltaic systems, and concluding remarks are presented in Section 5.

2. Mathematical modeling

The amount of light that is reflected from the interface of two materials depends on the refractive indices of the materials, the angle of incidence, and the polarization of light. The Fresnel equations give the values of reflection and transmission coefficients. For light passing through multiple layers of materials with different refractive indices, Fresnel coefficients can be used in conjecture with partial wave expansion to evaluate the reflectivity [20]. However, partial wave expansion method becomes overly complicated when the number of layers increases. In such cases, transfer-matrix based methods are more suitable [21]. The analysis in this paper is based on transfer-matrix method, as it is more general and can be extended to arbitrarily many layered systems easily.

For a s-polarized light transitioning between medium $i-1$ and medium i, the different electric field components, as shown in Fig. 2, are related through the equation [20]:

$$D_s(i-1)\begin{bmatrix} E_{i-1}^{+} \\ E_{i-1}^{-} \end{bmatrix} = D_s(i)\begin{bmatrix} E_i^{+} \\ E_i^{-} \end{bmatrix}. \tag{1}$$

The matrix $D_s(i)$ is given by:

$$D_s(i) = \begin{bmatrix} 1 & 1 \\ \frac{n_i}{Z_0}\cos\theta_i & -\frac{n_i}{Z_0}\cos\theta_i \end{bmatrix}, \tag{2}$$

where $Z_0 = \sqrt{\mu_0/\epsilon_0}$ is the intrinsic impedance of air, and $n_i = \sqrt{\epsilon_0\epsilon_i}$ is the refractive index of medium i.

Eq. (1) can be rewritten as:

$$\begin{bmatrix} E_{i-1}^{+} \\ E_{i-1}^{-} \end{bmatrix} = D_s([i-1]\,i)\begin{bmatrix} E_i^{+} \\ E_i^{-} \end{bmatrix}. \tag{3}$$

Here, $D_s([i-1]i) = D_s^{-1}(i-1)\cdot D_s(i)$. Using this iterative relation, the electric fields of ith layer can be related to the electric field of the first layer as [20,22]:

$$\begin{bmatrix} E_1^{+} \\ E_1^{-} \end{bmatrix} = M\begin{bmatrix} E_i^{+} \\ E_i^{-} \end{bmatrix}. \tag{4}$$

where

$$M = D_s(12)\cdot P_2\cdot D_s(23)\cdot P_3\cdots P_{i-1}\cdot D_s([i-1]i). \tag{5}$$

Here, the matrix P_i corresponds to the change of phase of the electric field as it travels from the top to bottom of the ith layer. If

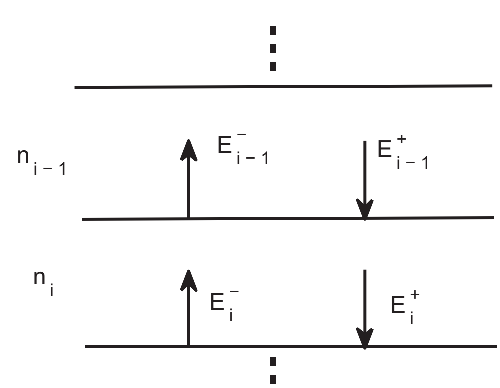

Fig. 2. Multilayer system showing the amplitude of electric fields in upward and downward directions in each layer.