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Research Article

Optimization of SiN_x Single and Double Layer ARC for Silicon Thin Film Solar Cells on Glass

M. Beye, M.E. Faye, A. Ndiaye, F. Ndiaye and A. Seidou Maiga
Laboratory of Electronics, Data Processing, Telecommunications and Renewable Energies (LEITER), UFR SAT University Gaston Berger, Saint-Louis Senegal

Abstract: The aim of this study is the optimization of the antireflection effect of SiN_x in silicon on glass based structure. A numerical calculation is performed and a SiNx double stack antireflection coating is found to have significant advantages over single-layer due to their broad-range coverage of the solar spectrum. Moreover, it was found that minimum reflection losses is obtained for SiN_x /SiN_x double-layer ARC with refractive indexes of 1.9 et 2.3 for the top and the bottom layer, respectively. The effect of the incident angle on reflectance is also studied. The numerical optimization procedure and its results are presented.

Keywords: Antireflection coating, double layer, SiN_x

INTRODUCTION

For the success of Photovoltaic (PV) cell technology, great advancements have to be made in both cost reduction and efficiency improvement. The use of light-trapping schemes is an approach that simultaneously achieves these two objectives since it allows cells to absorb sunlight using an active material layer that is much thinner than the material's intrinsic absorption length. This then reduces the amount of materials used in PV cells, which cuts cell cost in general. Moreover, light trapping can improve cell efficiency, since thinner cells provide better collection of photo-generated charge carriers.

Among many light trapping techniques, the depositing of a thin Antireflective Coating (ARC) is a commonly used one. An ideal antireflection structure should lead to zero reflection loss on solar cell surfaces over an extended solar spectral range for all incident angles. It is well known that normal-incidence reflection at a specific wavelength (usually 600 nm) can be minimized using a single layer coating with quarter-wavelength optical thickness when the refractive index is obtained as the square root of the product of the refractive indexes of the two surrounding media (Victoria *et al*., 2012; Schubert *et al*., 2008). However, a material with the required refractive index may not exist (Schubert *et al*., 2008) and additionally, single layer antireflection coatings cannot cover a broad range of the solar spectrum (Dhungel *et al*., 2006).

Dual stack antireflection coatings have significant advantages over single-layer due to their broad-range coverage of the solar spectrum. There have been reports of using double layer ARC based on two different materials (Dhungel *et al*., 2006; Remache *et al*., 2010; Wright *et al*., 2005; Liu, *et al*., 2010; Lijuan *et al*., 2011; Pettit *et al*., 1985; Lennie *et al*., 2009; Choi and Kim, 2010; Mahdjoub, 2007). However, using different materials is less cost effective since it often requires two deposition systems. Although using the same material is beneficial (Kumar *et al*., 2005), less work has been done on double layer coating of the same material (Lee *et al*., 2012; Gong *et al*., 2011; Kumar *et al*., 2005; Richards, 2003).

SiN_x is a proven material for ARC purpose since it has a high refractive index that can be easily varied between 1.9 and 2.3 by varying the deposition parameters (Lee *et al*., 2012; Gong *et al*., 2011). Moreover, SiN_x films are cost effective and exhibit an outstanding surface passivation quality (Gong *et al*., 2011).

In this study, a numerical optimization of the antireflection properties of SiN_x double layer is performed. The effect of the incident angle on the reflectance is also studied.

Basic principles of anti-reflective coating: Consider a homogenous, isotropic film with refractive index n_1 deposited on a substrate with refractive index n_s and placed in a medium with n_0, as shown in Fig. 1.

a) The incident beam undergoes an external reflection at the first interface
b) The transmitted beam undergoes an internal reflection and transmission at the second interface

Corresponding Author: A. Seidou Maiga, Laboratory of Electronics, Data Processing, Telecommunications and Renewable Energies (LEITER), UFR SAT University Gaston Berger, Saint-Louis Senegal

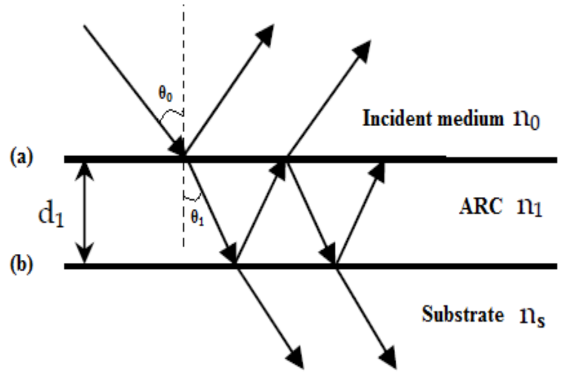

Fig 1: Reflection at the interface between two media

A good Anti-Reflective Coating (ARC) is vital for solar cell performance as it ensures a high photocurrent by minimizing reflectance.

While there are multiple ways to determine reflectance from thin films, such as the Rouard method (Lecaruyer *et al*., 2006) and the transfer matrix method (Dyakov *et al*., 2010; Bouhafs *et al*., 1998; Lijuan *et al*., 2011; Asghar *et al*., 2003; Zhan *et al*., 2011; Kosoboutskyy *et al*., 2010), the latter is the commonly used one.

According to the boundary conditions, the tangential components of the resultant electric and magnetic fields are continuous across the interface.

The field components at the first boundary (a) are related to those at the next (b) by the following expression:

$$E_a = E_b \cos(\delta) + B_b\left(\frac{i\sin(\delta)}{\gamma_1}\right) \tag{1}$$

$$B_a = E_b(i\gamma_1 \sin(\delta)) + B_b \cos(\delta) \tag{2}$$

where, $\delta = 2\pi n_1 d_1 \theta_1/\lambda$ is the phase difference that develops from one traversal of the film; θ_1 is the diffraction angle related to the incidence angle θ_0 by the Snell law: $n_0 \text{ Sin}\theta_0 = n_1 \text{ Sin}\theta_1$; γ_1 is the so-called optical admittance.

The last two equations can be written in matrix form:

$$\begin{bmatrix} E_a \\ B_a \end{bmatrix} = \begin{bmatrix} \cos(\delta) & \dfrac{i\sin(\delta)}{\gamma_1} \\ i\gamma_1 \sin(\delta) & \cos(\delta) \end{bmatrix} \begin{bmatrix} E_b \\ B_b \end{bmatrix} \tag{3}$$

The 2x2 matrix in (3) is called the transfer matrix.

For m layers coating system, each layer k has its own transfer matrix defined as:

$$M_k = \begin{bmatrix} \cos\delta_k & \dfrac{i\sin\delta_k}{\gamma_k} \\ i\gamma_k \sin\delta_k & \cos\delta_k \end{bmatrix} \tag{4}$$

where, $\delta_k = 2\pi n_k d_k \theta_k/\lambda$ is the phase difference that develops from one traversal of the k-layer, γ_k is the optical admittance of the k-layer. n_k, d_k (k = 1, 2, ... m) are the refractive index and thickness of the k layer, respectively.

In the case of oblique incidence, the admittance values of s polarization (TE) and p polarization (TM) are different. For the number k layer, they are:

$$\gamma_k = \begin{cases} n_k \cos\theta_k & \textit{for s polarisation} \\ n_k / \cos\theta_k & \textit{for p polarisation} \end{cases} \tag{5}$$

where, θ_k, as already mentioned, is given by the Snell law:

$$n_0 \sin\theta_0 = n_k \sin\theta_k \;;\; k = 1,2,\ldots,m \tag{6}$$

For this m layers coating system, the overall transfer matrix is the product of individual transfer matrices, taken in the order in which the light propagates through the multi-layer stack:

$$M_T = \prod_{k=1}^{m} M_k = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{7}$$

The reflection coefficient and the reflectance can then be expressed as:

$$r = \frac{\gamma_0 m_{11} + \gamma_0\gamma_s m_{12} - m_{21} - \gamma_s m_{22}}{\gamma_0 m_{11} + \gamma_0\gamma_s m_{12} + m_{21} + \gamma_s m_{22}} \tag{8}$$

$$R = |r|^2 \tag{9}$$

where γ_0 and γ_s, the admittance values for the incident medium and the substrate, are defined as γ_k.

The total reflectance *R* is defined as the average of the s and p components:

$$R = \frac{R_s + R_p}{2} \tag{10}$$

Optimization procedure: The structure under consideration is Glass/SiN_X/Silicon consisting of a crystalline silicon film (n_{Si} ~ 3.5) on borosilicate glass Borofloat 33, n_0 ~ 1.47 coated with a SiN_x thin film ARC in the superstrate configuration (SCHOOT and BOROFLOAT, 2010). The dispersion of silicon and borosilicate refractive indexes is neglected. The SiN_x refractive index varies from 1.9 to 2.3 (Lee *et al*., 2012; Gong *et al*., 2011).

Since the spectral response of silicon ranges from 300 to 1200nm, so only incident light in this wavelength range is considered.

We first considered quarter wavelength SiN_x single-layer thin film AR structures to find the optimal refractive index. Assuming optimal thickness for all the layers with the design wavelength λ = 600 nm, we simulated different AR structures of single layer. After finding the optimal refractive index, we used it in combination with the others to find the optimal double layer ARC. We also studied the effect of incident angle on the antireflection properties of the structures with the optimal single and double layer ARC.

RESULTS AND DISCUSSION

Figure 2 shows reflectance spectra for SiN_x single layer ARC of different refractive indexes under normal incidence. As can be seen, for a single layer ARC, the reflectance curve is V-shape, which means that the minimum reflectance can only be achieved in one specific wavelength. If the incident wavelength is far from this wavelength, the reflectance increases. Zero reflection is obtained only with n = 2.2 or n = 2.3. We can also note that for a SiN_x single layer the greater the refractive index, the better the anti-reflection effect.

Besides the normal incidence, the oblique incidence should also be considered since the antireflective coating is not always perpendicular to the incident light.

Figure 3 shows the results when a SiN_x single layer ARC with refractive index of 2.3 is used under different incident angles.

It can be seen from Fig. 3 that for this SiN_x single layer ARC the reflectance increase with the incident angle in the longer wavelength range. However, the increase is too high only for an incidence of 60°.

Figure 4 shows the reflectance curves when a SiN_x double layer stack is used as ARC under normal incidence.

As can be seen, the reflectance curve for this double ARC is W-shape. This means that the reflectance reaches a minimum at two specific wavelengths, indicating that, in the whole wavelength range, the antireflection effect of double layer ARC is better than that of single layer ARC. It can also be seen that the best result in obtained when the difference between the refractive indexes of the two layers is greater (n1 = 1.9 and n2 = 2.3). In this case, the reflectance is maintained fewer than 5% almost in the whole wavelength range.

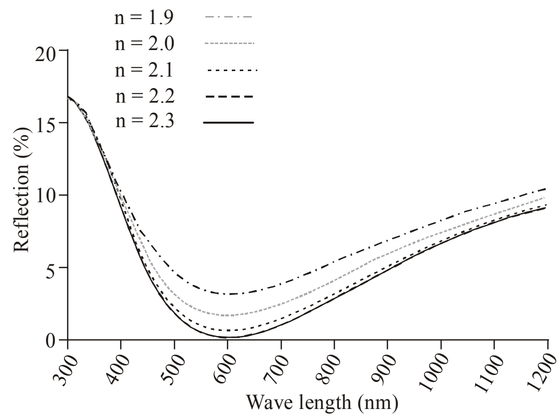

Fig. 2: Reflectance spectra for SiNx single layer ARC of different refractive indexes under normal incidence

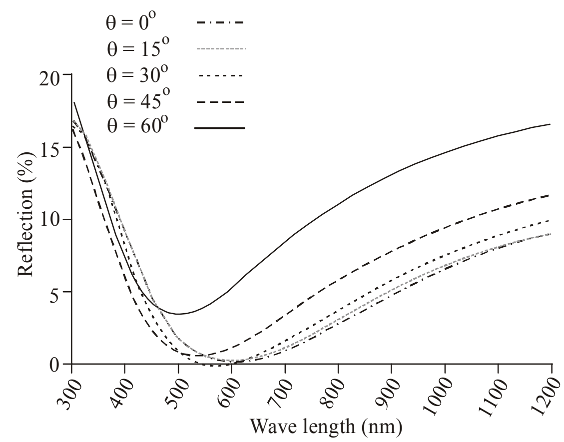

Fig. 3: Reflectance spectra for SiNx single layer ARC with refractive index of 2.3 under different incident angles

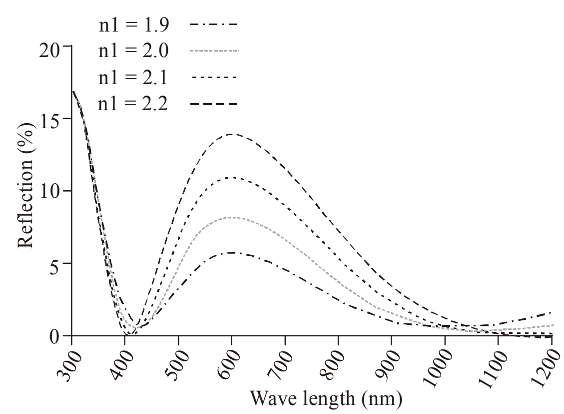

Fig. 4: Reflectance spectra for SiNx double layer ARC under normal incidence (when the bottom layer is the same in all cases; n2 = 2.3)

We further investigated the effect of the incident angle for this optimal layer combination. The results are shown in Fig. 5.

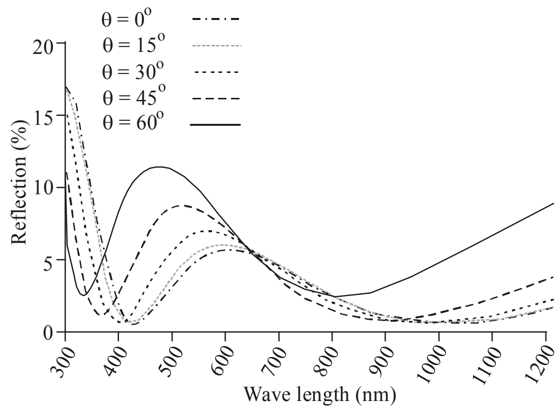

Fig. 5: Reflectance spectra for SiN_x double layer ARC (top layer n1 = 1.9 and bottom layer n2 = 2.3) under different incident angles

It can be seen from Fig. 5 that there is no general trend in the variation of reflectance with the incident angle. However, when the incident angles range from 0° to 30°, the reflectance curve is relatively stable. Even for the 60° incident angle, the reflectance in the whole wavelength range is still maintained below 12%.

CONCLUSION

It was found that the antireflection effect of SiN_x double-layer ARC is better than that of single layer. For SiN_x /SiN_x double-layer ARC, the optimal antireflection effect is obtained with refractive indexes of 1.9 and 2.3 for the top and the bottom layer, respectively. The incident angle is found to affect greatly the antireflection properties only beyond 30°. The results reported in this study can be used as a significant tool for efficiency improvement in thin film silicon solar cells on glass.

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