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Silicon nitride as antireflection coating to enhance the conversion efficiency of silicon solar cells

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Abstract: The aim of this work is to investigate the effect of single and double layer antireflection coating (ARC) on the performance of silicon solar cells. In this regard, various previous works on single and double layer ARCs have been consulted. Silicon nitride (Si_3N_4) has been used as ARC material because of its varying refractive index (1.8–3.0). Numerical calculations have been performed to obtain the reflectance for single and double layer Si_3N_4 using the transfer matrix method. Double layer antireflection coating (DLARC) of Si_3N_4 is found to have significant advantages over single layer antireflection coating (SLARC). Calculated reflectances have been further used in the PC1D simulator as external reflectance files to study the performance of a silicon solar cell. As a result of the simulation, the reflectance is found to reduce from >30% to <2% with short circuit current of 3.86 mA/cm^2 and conversion efficiency of 20.22% for DLARC. Results obtained for DLARC were further compared with a reference cell (without ARC), a cell with SLARC, and a cell with zero reflectance on the front surface.

Key words: Antireflection coating, PC1D, solar cell, reflectance, external quantum efficiency, conversion efficiency

1. Introduction

The main challenge regarding the performance of solar cells is reflection loss. When sunlight illuminates the front surface of a solar cell, some part of the light energy is transmitted into the cell and gets converted into electrical energy, whereas some part reflects from the front surface. In order to reduce the loss due to reflectance on the silicon surface, different methods have been used. Light trapping, surface texturing, and antireflection coatings (ARCs) are among the most widely used to reduce the loss due to reflection [1–4].

The reflectivity of bare silicon surface is quite high, i.e. more than 30% of incident light gets reflected from the silicon surface [5–7]. Thus, ARCs are of great importance to improve the efficiency of solar cells by reducing the loss due to reflection [5–9]. ARCs containing a single layer can be nonreflective only at a single wavelength, generally at the middle of the visible spectrum, whereas ARCs containing a double layer are effective over the whole visible spectrum [10]. Many works have been reported on ARCs with different materials such as MgF_2/SiNx by Dhungel et al. [11], SiO_2/TiO_2 by Lien et al. [12], Al_2O_3/TiO_2 by Bahrami et al. [13], MgF_2/Ti_2O_3 by Medhat et al. [14], and SiNx/SiNx by Beye et al. [15].

In this work, an attempt has been made to investigate the effect of single and double layer ARCs of Si_3N_4 on a silicon solar cell. Si_3N_4 has been used as ARC material for the following reasons:

- Its refractive index can be varied from 1.8 to 3.0 by varying the deposition parameters [9,16].

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- It exhibits outstanding surface passivation quality for refractive indexes above 2.3 [9].

- DLARC film of Si_3N_4 is also cost-effective.

The parameters of the solar cell (with DLARC) such as short circuit current, open circuit voltage, maximum power, EQE, and conversion efficiency are calculated and compared with a reference cell (without ARC), a cell with SLARC, and a cell with zero reflectance on the front surface.

2. Design of DLARC

Most solar cells are coated with ARC layers to reduce the reflection of light on the front surface of the cell [5,10]. A good ARC is one that ensures the high performance of a solar cell by reducing reflection and increasing photocurrent [10]. A set of optimized and well-designed ARCs on the front surface reduces the reflectivity on the front surface of the cell from 30% down to less than 2% [4,10]. Various methods are used to calculate the reflectivity of ARCs, such as the Fresnel formula, Rouard's method, and the transfer matrix method (TMM) [9,14,15]. The TMM is most commonly used as it relates the tangential components of electric and magnetic fields across the boundary of layers [15]. Thus, the transfer matrix (2 $\times$ 2) for a single film with refractive index n_1 on substrate with refractive index n_s is expressed as [17]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta & \frac{i\sin\delta}{\eta} \\ \eta(i\sin\delta) & \cos\delta \end{bmatrix} \begin{bmatrix} 1 \\ \eta_s \end{bmatrix}, \tag{1}$$

where $\delta = \frac{2\pi n_1 d_1 \cos\theta_1}{\lambda}$ is the phase thickness of film, d_1 is the thickness of film, θ_1 is the diffraction angle related to the incidence angle θ_o by Snell's law: $n_o \sin\theta_o = n_1 \sin\theta_1$, and η is the optical admittance with parallel and perpendicular components $\eta_{\|} = (\sqrt{E_o/\mu_o n})/\cos\theta$ and $\eta_{\perp} = \sqrt{E_o/\mu_o n\cos\theta}$, respectively.

Single layer antireflection coating (SLARC) is effective at one wavelength only while double layer antireflection coating (DLARC) is effective over a wide range of wavelengths [10]. Thus, the above analysis (TMM) is extended over DLARC as [17]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{\eta_1} \\ \eta_1(i\sin\delta_1) & \cos\delta_1 \end{bmatrix} \begin{bmatrix} \cos\delta_2 & \frac{i\sin\delta_2}{\eta_2} \\ \eta_2(i\sin\delta_2 & \cos\delta_2 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_s \end{bmatrix}. \tag{2}$$

This gives the reflection coefficient and reflectance for a given assembly as [17]:

$$r = \frac{\eta_o m_{11} + \eta_o \eta_s m_{12} - m_{21} - \eta_s m_{22}}{\eta_o m_{11} + \eta_o \eta_s m_{12} + m_{21} + \eta_s m_{22}}, \tag{3}$$

$$R = |r|^2, \tag{4}$$

where m_{11}, m_{12}, m_{21}, and m_{22} are the elements of the characteristics matrix obtained by multiplying the two matrices representing two layers. η_o and η_s, are the admittance values of incident medium and the substrate.

3. Device simulation

The PC1D simulator is used to study the electrical and optical parameters of the silicon solar cell. PC1D has two files (“one-sun.exe” and “scan-qe.exe”) that contain standard parameters that are used during the simulation of a solar cell. The “one-sun.exe” file gives short circuit current, maximum power, and open circuit voltage while the “scan-qe.exe” file gives reflectance, internal quantum efficiency, and external quantum efficiency versus wavelength. This program also accepts the reflectance as an external file, which provides an opportunity to include the desired reflectance file. Figure 1 shows the PC1D-based simulation model of a silicon solar cell. Refractive index and thickness of the ARC material used are presented in Table 1.

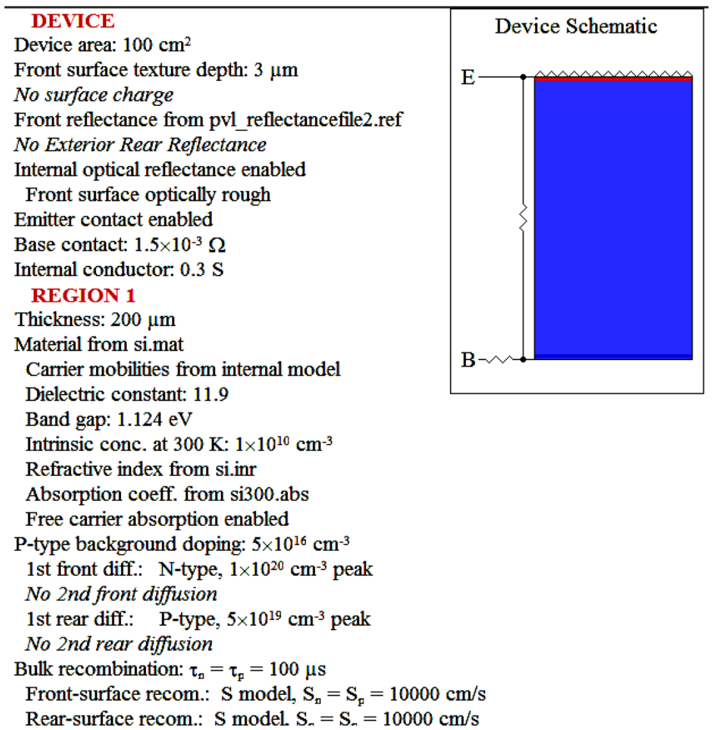

Figure 1. Summary of simulation parameters for PC1D model.

Table 1. Refractive index and thickness of ARC films used for simulation.

Layer	n_1 (d_1) Si_3N_4	n_2 (d_2) Si_3N_4
SLARC	-	2.0 (75 nm)
DLARC	1.8 (83.3 nm)	2.99 (50.2 nm)

4. Results and discussion

4.1. Reflectance

Figure 2 shows the variation of reflectance as a function of wavelength for a bare silicon cell as well as a cell coated with SLARC of quarter wavelength thickness from Si_3N_4 under normal incidence. In this work all coatings have been designed to hold minimum reflection for the incident wavelength of 600 nm. Spectral irradiance of AM 1.5 global spectrum (in W/m^2 nm) as a function of wavelength is also presented in Figure 2. It can be observed that reflectance has been reduced considerably from more than 30% for the bare silicon cell down to less than 0.5% for the silicon cell coated with Si_3N_4. It can also be observed that the reflectance is minimum at only one wavelength (600 nm) and is high for other wavelength values. Furthermore, the reflectance calculated above using TMM has been used in the PC1D simulator to study the performance of the silicon solar cell. Figure 2 show good agreement between the numerically calculated reflectance and that obtained from PC1D. Thus, it is observed that the SLARC reduces reflectance, which in turn increases the EQE as well as short circuit current due to increase in the absorption of photons from incident light. Table 2 shows that the efficiency of the silicon solar cell without ARC is 13.12%, whereas it becomes 19.6% with SLARC.

Table 2. Photovoltaic data of silicon solar cell without and with ARCs under AM 1.5 irradiation (PC1D).

ARC	I_{sc}	V_{oc}	FF	η (%)
No ARC	2.585	0.652	0.78	13.12
Si_3N_4	3.731	0.662	0.79	19.60
Si_3N_4/Si_3N_4	3.863	0.663	0.79	20.22
Zero Refl.	4.007	0.664	0.78	20.78

SLARC has one disadvantage in that it can minimize reflectance at one wavelength only and not over the broad range of solar spectra. This problem can be solved by applying two or more layers of ARC to the solar cell. In the present case, to achieve minimum reflectance over a wide range of solar spectra, a double layer of Si_3N_4 has been used on the front surface of the silicon solar cell. The reflectance for Si_3N_4/Si_3N_4 has been calculated numerically using TMM. Figure 3 shows the variation of reflectance for DLARC as a function of wavelength. From this plot one can observe that the reflectance reduces to $<10\%$ over a wide range of spectra (i.e. for wavelengths of 400–1100 nm) and becomes less than 2% for wavelengths of 500–900 nm. The performance of the silicon solar cell with DLARC has been evaluated using PC1D. Results obtained from simulations are presented in Figure 3 and Table 2. These results show that the performance of the solar cell is improved considerably with the use of DLARC of Si_3N_4 on the front surface of the cell and the efficiency of the cell become 20.22%.

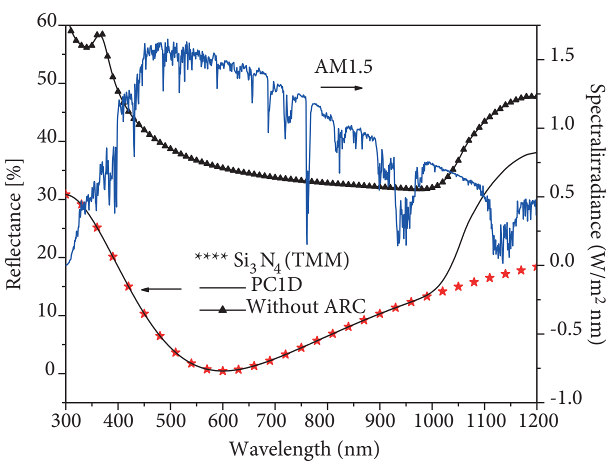

Figure 2. Variation of reflectance and spectral irradiance as a function of wavelength.

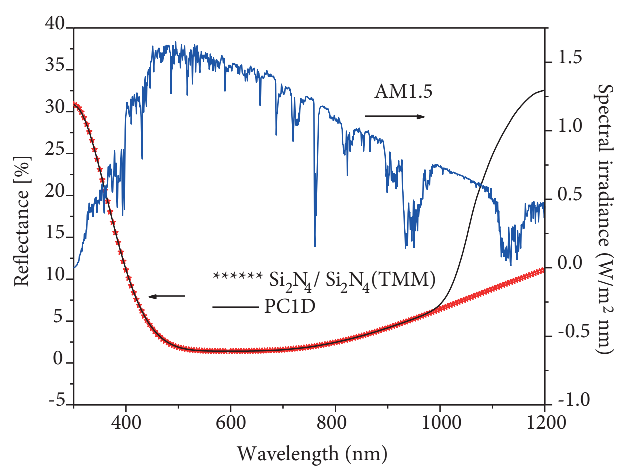

Figure 3. Plot shows the variation of reflectance for DLARC and spectral irradiance as a function of wavelength.

4.2. External quantum efficiency

The quantum efficiency of a solar cell is a vital factor as it relates an optical parameter (reflectance) to electrical parameters (short circuit current and conversion efficiency) and all these can be improved by applying a proper ARC [9]. Quantum efficiency of a cell is defined as the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on it. Thus, the performance of ARC can be analyzed in terms of reflectance and EQE (i.e. if the reflectance is zero then EQE is 100%). EQE curves as a function of wavelength for cells with zero reflectance, without ARC, and with SLARC and DLARC are shown in Figure 4. The graph shows a good improvement in the EQE of the solar cell with DLARC as compared to SLARC and is almost in accordance with the EQE for zero reflectance over a wide range of solar spectra.

4.3. Electrical parameters

As a result of improvement in the optical parameters (i.e. reflectance and quantum efficiency), good improvement is expected in the electrical parameters of the solar cell. The characteristic I-V curves of the solar cell without ARC, with SLARC (Si_3N_4), with DLARC (Si_3N_4/ Si_3N_4), and with zero reflectance are shown in Figure 5. The plot shows a significant improvement in the short circuit current due to the change in the ARC layers. The maximum current is achieved for DLARC (Si_3N_4/ Si_3N_4) and is very close to that of the solar cell with zero reflectance. The short circuit current, open circuit voltage, fill factor, and photovoltaic efficiency of the silicon solar cell corresponding to various ARCs are presented in Table 2.

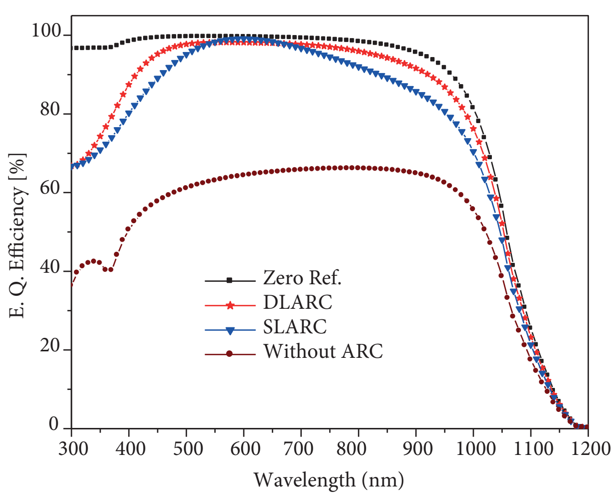

Figure 4. Plot shows variation of external quantum efficiency as a function of wavelength.

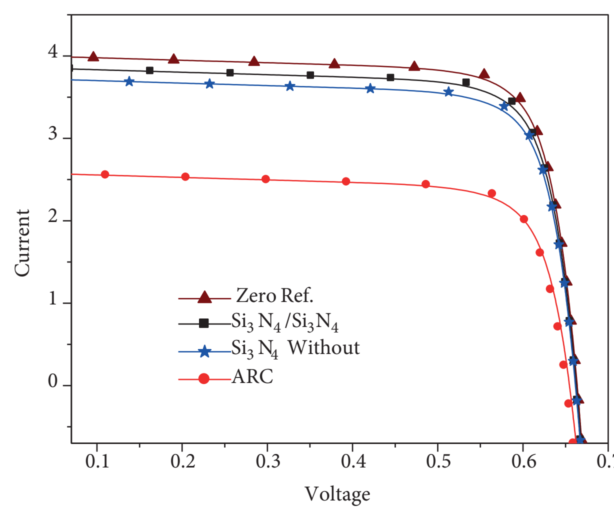

Figure 5. Plot shows variation of short circuit current as a function of open circuit voltage.

5. Conclusion

In the present work, the effect of Si_3N_4 as single and double layer ARC on the surface of silicon solar cells was investigated. Results show that single layer ARC gives maximum conversion efficiency at a single wavelength. However, double layer ARCs give maximum efficiency over a wide spectral range. Finally, it has been demonstrated that low weighted reflectance can be achieved by applying DLARC of Si_3N_4, which will also improve I_{sc} from 2.585 to 3.863 along with photovoltaic efficiency of about 20.22%.

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