ISSN 2347 - 3983
Volume 10. No.3, March 2022
International Journal of Emerging Trends in Engineering Research
Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter051032022.pdf
https://doi.org/10.30534/ijeter/2022/051032022

Design and Simulation of Triple Layer Antireflection Coating for Silicon Solar Cells

R Sharma
Department of Engineering Physics, Model Institute of Engineering and Technology,
Jammu – India.
rbasotra@yahoo.com

Received Date February 8, 2022 Accepted Date : February 28, 2022 Published Date : March 07, 2022

ABSTRACT

In present work an attempt has been made to investigate the effect of triple layer anti-reflection coating (TLARC) on the surface of silicon cell theoretically. In this regard, MgF_2, Si_3N_4, and TiO_2 have been used to design anti-reflection coatings (ARC). Reflection spectra for single double and triple layer ARCs have been evaluated numerically using transfer matrix method (TMM). Numerically calculated reflection spectra for single, double, and triple layer anti-reflection coatings further used in PC1D simulator to study the performance of silicon solar cell. Result shows reduction in reflectance of silicon solar cell down to less than 3% in the wavelength range 400 – 1200 nm with conversion efficiency 21.6% for TLARC ($MgF_2/Si_3N_4/TiO_2$).

Key words: Reflectance, silicon solar cell and conversion efficiency, TLARC, PC1D.

1. INTRODUCTION

Optical devices are always accompanied with optical losses such as reflection, absorption and scattering of which reflection loss is major. Solar cell is also an optical device used to harvest solar energy. But the main challenge regarding the performance of solar cell is the loss of light energy due to reflection from front surface. For bare silicon reflectivity is quite high i.e., more than 30% of incident light reflects from the silicon surface [1, 2]. Antireflection coatings (ARC) are widely used on the top surface of solar cells to reduce reflection loss and hence to improve their performance [1, 2, 3]. Since the fabrication of solar cell, researchers are using different ARCs and still searching for a suitable one to improve the efficiency of solar cell [4, 5]. An ideal antireflection coating can reduce the reflection loss considerably over wide range of spectra. In the recent past, many researchers have investigated single- and double-layer antireflection coatings, theoretically as well as experimentally such as: Effect of single and double layer ARCs of different materials by R. Sharma et al. [2], G Hashmi et al. [3] investigated the impact of different ARCs using PC1D, SiO_2/TiO_2 by Lien et al. [6], Al_2O_3/TiO_2 by Bahrami et al. [7], $MgF_2/Ti_2O_3$by M. Medhat et al. [8] and SiNx/SiNx by R. Sharma [9].

Usually, single layer antireflection coating (SLARC) is non-reflective at single wavelength only, generally at the mid of visible spectrum. Since the spectral response of silicon solar cell ranges from 300 – 1200 nm, so they required a broadband ARC [10]. Also, performance of an ARC depends on the various factors such as: 1) the number of layers, 2) thickness of each layer, 3) range of incident spectrum and 4) the angle of incidence [11]. Thus, use of multilayer antireflection coatings would be more effective over wide range of spectra. A very few reports on the multilayer antireflection coating are available such as: SiO_2-Si_3N_4-TiO_2 and TiO_2-SiO_2-TiO_2 by U. Sikder et al. [12], SiO_x-SiO_xN_x-SiN_x:H by N. Sahouane et al. [13], MgF_2-Al_2O_3-ZnS by Z. Feng et al. [14].

In present work an attempt has been made to investigate the effect of triple layer anti-reflection coating on the surface of silicon solar cell. MgF_2, Si_3N_4, and TiO_2 are used to design single, double, and triple layer anti-reflection coatings. Si_3N_4 is used to design single, double, and triple layer ARCs, as its refractive index vary from 1.8 – 3.0 [9, 13]. All reflectance spectra are obtained using transfer matrix method.

2. MODELING OF ARCs

Transfer matrix is commonly used method to obtain the reflectivity of ARC as this relates the tangential components of electric and magnetic fields across the boundary of layers [5, 7]. Transfer matrix for single layer system at normal incidence is expressed as [9, 12, 15, 16]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{\eta_1} \\ n_1(i\sin\delta_1) & \cos\delta_1 \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (1)$$

where $\delta_1 = \frac{2\pi n_1 d_1 \cos\theta_1}{\lambda_o}$ is phase thickness of film, $d_1 = \frac{\lambda_o}{4n_1}$ is the thickness of film, θ_1 is the diffraction angle related to the incidence angle θ_o by the Snell's law: $n_o \sin\theta_o = n_1 \sin\theta_1$.Thus, reflectance for given assembly can be expressed as [15, 16].

$$R = \left| \frac{1 - Y/n_0}{1 + Y/n_0} \right|^2$$

where $Y = C/B$. Further, at normal incidence transfer matrix for double layer antireflection coating (DLARC)and triple layer antireflection coating (TLARC) can be expressed as [9, 16]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{n_1} \\ n_1(i\sin\delta_1) & \cos\delta_1 \end{bmatrix} \begin{bmatrix} \cos\delta_2 & \frac{i\sin\delta_2}{n_2} \\ n_2(i\sin\delta_2 & \cos\delta_2 \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \frac{i\sin\delta_1}{n_1} \\ n_1(i\sin\delta_1) & \cos\delta_1 \end{bmatrix} \begin{bmatrix} \cos\delta_2 & \frac{i\sin\delta_2}{n_2} \\ n_2(i\sin\delta_2 & \cos\delta_2 \end{bmatrix} \begin{bmatrix} \cos\delta_3 & \frac{i\sin\delta_3}{n_3} \\ n_3(i\sin\delta_3 & \cos\delta_3 \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (3)$$

For SLARC at normal incidence, to achieve zero reflection, refractive index of material can be expressed as $n_1 = \sqrt{n_o n_s}$ [3]. For DLARC, at normal incidence on layers with quarter-wavelength and substrate should satisfy the following condition to achieve zero reflection [8].

$$\left(\frac{n_2}{n_1}\right)^2 = \frac{n_s}{n_0} \quad (4)$$

Available materials that satisfy above condition nearly are MgF_2 and Si_3N_4. Further, for TLARC to achieve minimum reflection (i.e., R ≈ 0), the refractive index of each layer can be expressed as [16]:

$$n_1^4 = n_o^3 n_s \quad \text{or} \quad n_1 = (n_o^3 n_s)^{1/4}$$

$$n_2^4 = n_o^2 n_s^2 \quad \text{or} \quad n_2 = (n_o^2 n_s^2)^{1/4} \quad (5)$$

$$n_3^4 = n_o n_s^3 \quad \text{or} \quad n_3 = (n_o n_s^3)^{1/4}$$

Thus, for silicon (n_s = 3.58), according to eq (5), the refractive index for top layer is 1.38 (MgF_2), for middle layer 1.89 (Si_3N_4) and for bottom layer 2.60 (TiO_2). Value of refractive index for silicon is selected in accordance with PC1D and $n_o = 1$ is the refractive index for air.

3. DEVICE SIMULATION

Simulation plays a vital role both to improve the existing devices as well as to develop new one. Over years various solar cell modeling tools have been developed such as: AMPS, PC1D, ASA, SCAPS and AFORS-HET etc. Among all, PC1D simulator is widely (more or less) accepted as standard in the field of PV technology. In present work PC1D software is used to simulate silicon solar cell with and without ARC. This program also accepts the reflectance as an external file, which provides opportunity to include desired reflectance [9, 15]. Table 1 show parameters used to simulate silicon solar cell in PC1D simulator.

Table 1: Parameters used in PC1D software to simulate silicon solar cell

Device Parameters	Value
Device area	100 cm^2
Front surface	Textured
Texturing angle and depth	54.74° and 3 µm
Exterior reflectance	External
Light source	One sun (AM 1.5, 100mW/cm^2)
Layer Parameters	**Value**
Thickness	200 µm
Material	Silicon
Background doping	$5×10^{16}$ cm^{-3}, p-type
Resistivity of base	0.4 Ω. Cm
Emitter peak doping	$3×10^{20}$ cm^{-3}, n-type
Doping profile and depth factor	Erfc and 0.1µm
Emitter sheet resistance	56 Ω/sq
BSF	$5×10^{19}$ cm^{-3}, p-type

4. RESULT AND DISCUSSION

Characteristic reflectance curves for silicon solar cells with and without ARCs are shown in Figure 1. Detail of ARC layers such as: material, refractive index and layer thickness are presented in Table 2. From figure one can observe the reflectance for bare silicon is greater than 30% over entire spectral range (300 – 1200 nm) whereas with SLARC (Si_3N_4) reflectance reduced appreciably and become zero at 600 nm. But major drawback of SLARC is that this cannot minimize reflection over broad range of solar spectra. Moreover, materials of required refractive indexes are very limited or may not exist. So, this problem of SLARC can be addressed by applying two or more layers of ARC on the front surface of silicon solar cell [2].

Figure 1 shows DLARC (MgF_2/Si_3N_4) is capable to reduce reflectivity close to zero in wavelength range 500-700 nm whereas below 500 nm and above 700 nm reflection is still high. This shows DLARC is effective as compare to SLARC but still for large portion of solar spectra, reflection is high. Therefore, low reflectivity over entire range of spectra can be achieved by using TLARC of suitable refractive indices. Reflectance as a function of wavelength for TLARC ($MgF_2/Si_3N_4/TiO_2$) is also shown in Figure 1. Graph shows total reflectance for TLARC is reduces below 3% over wide range of solar spectra (400 – 1200 nm). Finally, calculated reflectance data for various ARCs have been used in PC1D software as external reflectance files to study the performance (optical and electrical parameters) of silicon solar cell. Figure 1 shows a good agreement between reflectance curves calculated using TMM and obtained from PC1D in the wavelength range 300 - 1000 nm (corresponding to the active band of silicon).

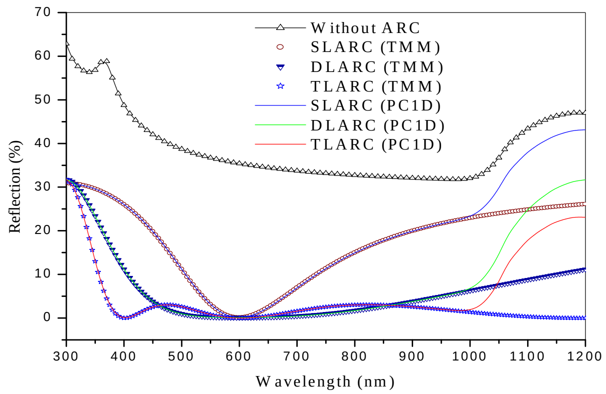

Figure 1: Variation of reflection as a function of wavelength for silicon solar cell with SLARC (Si_3N_4), DLARC (MgF_2/Si_3N_4) and TLARC ($MgF_2/Si_3N_4/TiO_2$) as well as without ARC.

Quantum Efficiency is another important parameter of solar cell which relates electrical parameters of solar cell such as short circuit current, open circuit voltage and conversion efficiency with optical parameters (reflectivity) [13]. An ideal ARC is one which ensures high photocurrent by decreasing reflection. Thus, an ARC can be analyzed in terms of reflectance and EQE i.e., for zero reflectance, EQE will be 100% [9]. External quantum efficiency curves as a function of wavelength for silicon solar cell with SLARC, DLRC and TLARC are shown in Figure 2. From figure one can clearly observe there is significantly improved in EQE of solar cell with TLARC. Further, on the account of improvement in the optical parameters (reflectance & quantum efficiency), good improvement in electrical parameters is expected. The short circuit current, open circuit voltage, fill factor and photovoltaic efficiency of the silicon solar cell corresponding to different ARCs and without ARC have been presented in Table 3. Result shows TLARC lead to increase in conversion efficiency of silicon solar cell over DLARC.

Table 2: Refractive index and thickness of ARC films used for simulation.

ARC	n_1 (d_1 in nm)	n_2 (d_2 in nm)	n_3 (d_3 in nm)
Si_3N_4	1.9 (78.9)	-	-
MgF_2/Si_3N_4	1.38 (108.7)	2.69 (55.8)	-
$MgF_2/Si_3N_4/TiO_2$	1.38 (108.7)	1.9 (78.9)	2.6 (57.7)

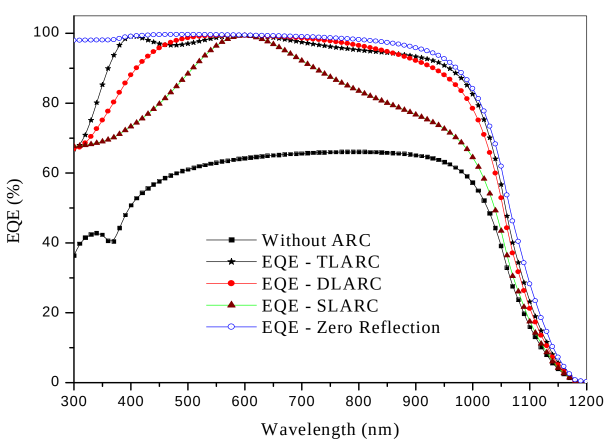

Figure 2: External quantum efficiency (EQE) of silicon solar cell as a function of wavelength (PC1D).

Table 3: Photovoltaic data of silicon solar cell under AM 1.5.

ARCs	Jsc (mA/cm^2)	Voc (Volt)	FF (%)	η (%)
No ARC	26.17	0.66	78.00	13.6
SLARC	35.28	0.67	79.3	18.8
DLARC	39.38	0.67	79.5	21.0
TLARC	39.81	0.68	79.8	21.6

5. CONCLUSION

In the present work, transfer matrix-based model has been demonstrated to design and simulate triple layer antireflection coating. TLARC is found to be non-refractive over wide range of wavelength (400 – 1200 nm) over DLARC which is non-refractive from 500 – 700 nm. As a result, external quantum efficiency (EQE) of solar cell with TLARC becomes identical to the ideal cell (cell with zero reflection on the surface) especially at low wavelengths. Finally, it has been demonstrated that low weighted reflectance can be achieved by applying TLARC, which in turn will improve conversion efficiency of silicon solar cell.

REFERENCES

[1] Ali K, Sohali A, Sohali M Z, Jafri M; *Int. J. Electrochem. Sci.*, 9 7865 (**2014**).

[2] Sharma R, Gupta A, Virdi A; *J. Nano- Electron Phys.*, 9 (**2017**).

[3] Hashmi G, Rashid M J, Mahmood Z H, Hoq M, Rahman M H; *J. Theoretical App. Phys.*, 12, 327 (**2018**).

[4] Uzum A, Kuriyama M, Kanda H, Kimura Y, Tanimoto K, Fukui H, Izumi T, Harada T, Ito S; *Int. J. Photo energy* (**2017**).

[5] Abdullah H, Lennie A, Ahmad I; *J. Appl. Sci.*, 9, 1180 (**2009**).

[6] Lien S, Wun D, Yeh W, Liu J; *Sol. Energ. Mat. Sol. Cells*, 90, 2710 (**2006**).

[7] Bahrami A, Mohammadnejad S, Abkenar N J, Soleimaninezhad S; *Int. J. Renew. Energ. Res.*, 3, 79 (**2013**).
[8] Medhat M, EL-Zaiat S, Farag S, Youssef G; *Turkish Journal of Physics*, 40, 30 **(2016)**.
[9] Sharma R; *Turkish Journal of Physics*, 42, 350 (**2018**).
[10] Daniel N, Wright, Erik S, Marstein, Holt A; *IEEE Photovoltaic Specialists Conf.* (**2005**).
[11] Mousa H M, Shabat M M, Karmoot M R; *Romanian Reports in Phys.*, 72, 416 (**2020**).
[12] Sikder U, Zaman M A; *Optics & Laser Techno.*, (**2016**)
[13] Sahouane N, Zerga A; *Energy Procedia*, 44, 118 (**2014**).
[14] Feng Z, Hai-Li W, Ji-Fang H, Juan W, She- Song H, Hai-Qiao N, Zhi-Chuan N; *Chin. Phys. Lett.*, 28, (**2011**).
[15] Sharma R; *Heliyon (Elsevier)*, 5 (**2019**); https://doi.org/10.1016/j.heliyon.2019.e01965
[16] Macleod H A; *Thin Film Optical Filters*, London: Institute of Physics (**2001**).