

Impact of Anti-Reflective Coating on Silicon Solar Cell and Glass Substrate : A Brief Review

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ABSTRACT: The most important factor in enhancing the performance of an optical device is to minimize reflection and increasing transmittance of light for a broad wavelength range. The choice of appropriate coating material is crucial in decreasing reflection losses at the substrate. The purpose of this review is to highlight anti-reflection coating (ARC) materials that can be applied to silicon solar cell and glass substrate for minimizing reflection losses. The optical and electrical behavior of ARC on a substrate is highly dependent on thickness and refractive index (RI) of ARC films that are being deposited on it. The coating techniques and performance of single and multi-layered ARC films after coated on a substrate in a wide range of wavelength spectrum will be studied in the paper.

Key words: Anti-Reflection Coating, Silicon solar cell, Glass, Reflective index, Wavelength

Subscript

ARC: Anti-Reflective Coating

RI: Reflective Index

1. Introduction

In PV systems, about 30% of the sun's energy normally reflected back to air after striking from the panel's surface while 70 % of energy could be able to make its path to solar cells¹⁾. Reflection occurs when two mediums have a variable RI. So when RI of both medium is close to one another, less light will be reflected back. However, there will be no reflection if RI of coated material is the same as that of the surrounding air²⁻⁴⁾. The more is the angle of incident light are far away from normal, the more is the light reflection⁵⁾. Anti-Reflection Coating (ARC) is generally applied to those devices where light reflection is a major issue. The focal hurdle in a PV device's fabrication is minimum conversion of energy efficiency, it can be developed by semiconductor and advanced material micro-fabrication^{6,7)}. For this purpose, the usage of ARC has been very effective to provide better transmission and to minimize reflection⁸⁾. The common procedure to minimize the reflection is to coat the

substrate with the material having appropriate RI and an optimized thickness^{9,10)}. A variety of materials could be utilizes as ARC film in silicon solar cells such as Al_2O_3 , SiO_2 , ZnS , TiO_2 , MgF_2 , etc. and a combination of these materials. The inappropriate selection of ARC films and partial understanding of their specification can cause an increase in reflection, a reduction in transmittance of light and hence lower the efficiency of a solar cell. In this review paper, we categorized ARC film into single and multi-layered coating.

2. Single Layered ARC

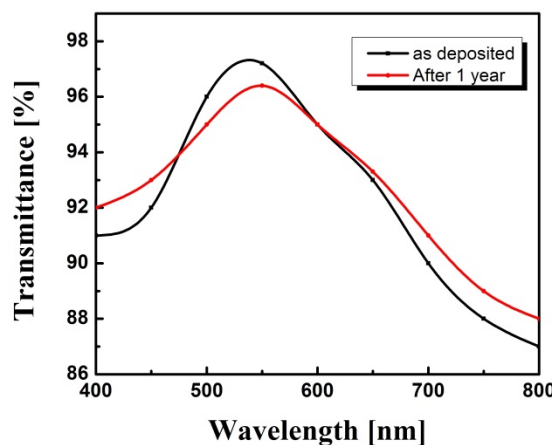
Sagar et al. investigated performance of single layered (SL) ZnO , MgO and Al_2O_3 material as ARC on silicon solar cell substrate after depositing using RF sputtering¹¹⁾. The thickness of MgO , ZnO and Al_2O_3 set to be 85, 95 and 80 nm respectively. The electrical characterizations of coated films were examined by solar simulator (Sol3A Class AAA) and transmittances were measured by UV visible spectrometer (Shimadzu MPC3600). The measured transmittance spectrum of ZnO was 95% at 412 nm, for MgO it was 92% at 373 nm and for Al_2O_3 it was 93% at 356 nm. Table 1 show results obtained from solar simulator.

Mahadik et al. prepared SiO_2 SLARC through sol-gel process by using tetraethoxysilane (TEOS), Triton X-100 and Polyethyleneglycol (PEG) as polymeric porogens materials¹²⁾. UV spectrometer (PerkinElmer, Lamda 750) was used to measure

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Table 1. Electrical properties of coated films

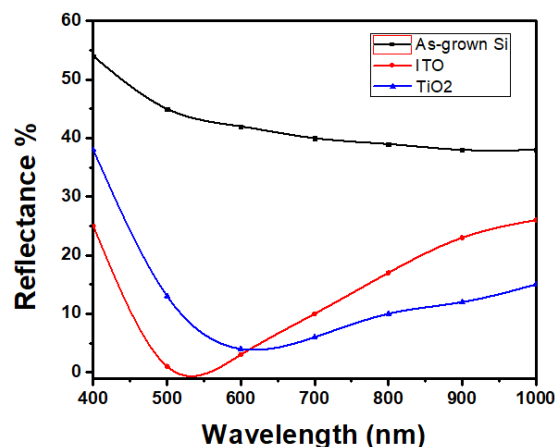
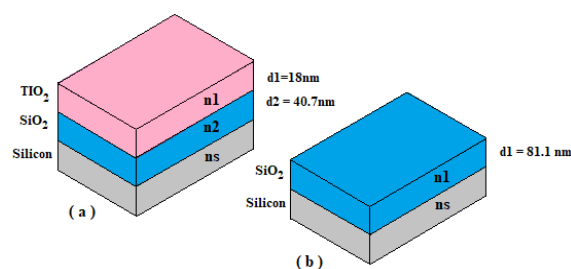
Properties	ZnO	MgO	Al ₂ O ₃
V _{oc} (V)	0.564	0.571	0.562
I _{sc} (A)	0.026	0.027	0.026
J _{sc} (mA/cm ²)	25.656	26.455	26.484
FF	66.603	64.064	61.225
Efficiency (%)	9.633	9.864	9.125

**Fig. 1.** Transmittance before and after air exposure

the transmittance at the broad band range of 300-900 nm. The coating exhibits the RI of 1.39 and for thickness of ~100 nm. The calculated transmittance at soda lime glass substrate after applying coating was observed to be 97.5% at wavelength of 500 nm. However, the coated substrate showed an increase in transmittance of about 6% in 400-600 nm wavelengths as compared to bare substrate. Attenuation in average transmittance of 0.6% was recorded after exposing the coated substrate in air as it is shown in Fig. 1.

Zhu, Li Qiang, *et al.* deposited Al₂O₃ on n-type crystalline silicon wafer by Atomic Layer Deposition (ALD) by the use of Al(CH₃)₃ and H₂O as precursors¹³. They obtained average reflectance between 2.8% to 4.2% on thickness range of Al₂O₃ from 100 nm to 70 nm. Optical characteristics of coated Al₂O₃ have been investigated through spectroscopic ellipsometry. They obtained carrier life time of about ~4.5 ms and effective surface recombination velocity of ~4 cm/s by depositing 100 nm layer of Al₂O₃.

Ali *et al.* deposited titanium dioxide (TiO₂) and indium tin oxide (ITO) ARC films on p-type monocrystalline silicon cell by using radio frequency magnetron sputtering¹⁵. The width of TiO₂ from 55 to 60 nm and ITO from 60 to 64 nm was used. The deposited layers on the substrate were analyzed by Raman Spectroscopy, X-ray Diffraction (XRD), Energy Dispersive

**Fig. 2.** Percentage reflectivity by layers with wavelength range**Fig. 3.** a) SiO₂ b) SiO₂/TiO₂

Spectroscopy (EDS), Field Emission Scanning Electron Microscopy (FESEM) and Atomic Force Microscopy (AFM). They measured overall optical reflectance in the wavelength range of 400-1000 nm which was about 12% for ITO and 10% for TiO₂ as shown in Fig. 2. Moreover, improvements in the measurements of reflectance were observed to be 25% for ITO and 23% for TiO₂ as compared to as-grown silicon.

3. Double Layered ARC

Ali *et al.* performed a sputtering procedure at room temperature for the preparation and evaluation of SLARC (SiO₂) and double layered (DLARC) (SiO₂/TiO₂) on silicon solar cells¹⁴. They investigated the elemental analysis of SiO₂ and SiO₂/TiO₂ by the use of EDS while surface morphology appearance was composed by FESEM. Structural diagram of SiO₂ and SiO₂/TiO₂ have been shown in Fig. 3.

d1 and d2 shows thickness of layers while n₀, n₁, n₂ and n_s shows the RI of air, outer layers, inner layer and silicon substrate. For achieving zero reflective scenarios, the condition of the equation should be fulfilled.

$$\frac{n_2 d_2}{\lambda_o} = \frac{1}{2\pi} \tan^{-1} \left\{ \pm \left[\frac{(n_s - n_o)(n_o n_s - n_1^2) n_2^2}{(n_1^2 n_s - n_o n_2^2)(n_2^2 - n_o n_s)} \right]^{1/2} \right\} \quad (1)$$

$$\frac{n_1 d_1}{\lambda_o} = \frac{1}{2\pi} \tan^{-1} \left\{ \pm \left[\frac{(n_s - n_o)(n_o n_s - n_2^2) n_1^2}{(n_1^2 n_s - n_o n_2^2)(n_1^2 - n_o n_s)} \right]^{1/2} \right\} \quad (2)$$

It was observed that SiO₂ and SiO₂/TiO₂ coatings show reflectance of 15% and 7% respectively for the broad band range of 400-1000 nm. Minimum reflectance of 2.3% has been shown at the wavelength of 630 nm. So, by using double layered SiO₂/TiO₂, 37% improvement in efficiency is recorded for mono crystalline silicon solar cell.

Dhungel. Suresh Kumar, et al. applied DLARC using MgF₂ and SiN_x on silicon solar cells¹⁶. They deposited 75 nm thick layer of MgF₂ having RI of 1.38 over 72 nm SiN_x thick film having RI of 2.05 by using thermal evaporation under high vacuum of 10⁻⁶ Torr. By using these ratios of thickness of SiN_x and MgF₂ revealed meaningful performance having conversion efficiency of 16.01% for multicrystalline and 16.94% for single crystalline solar cell respectively. Fig 4 shows the effect of reflectance over SiN_x with and without MgF₂ film.

Jung, Jinsu, et al. successfully deposited DLARC (TiO₂/Al₂O₃) using sol-gel process on p type Si solar cells and annealed at 400 °C¹⁷. The fabricated solar cells having DLARC achieved the efficiency of about 13.95% having an open circuit voltage (V_{OC}) of 593.35 mV, short circuit current of 35.27 mA/cm² and fill factor (FF) of 66.67%. Lowest reflectance showed by DLARC of about 3.02% at 970 nm. These coated films showed lower average reflectance of 4.74% in the broad-band range of 400 nm to 1000 nm. Moreover, the cell having DLARC shows relatively low value of series resistance as compared to SLARC.

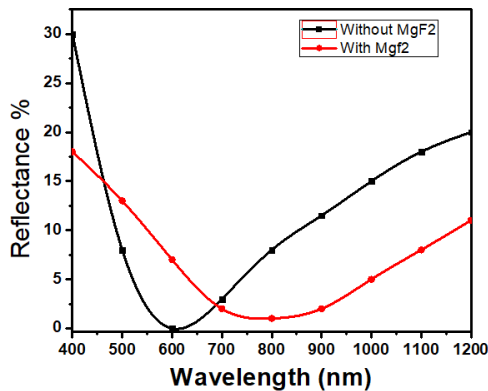


Fig. 4. Reflectance spectrum of single and double layered films

Medhat, Mohamed investigated the effect of TiO₂ and MgF₂ as DLARC on silicon solar cell using simulations¹⁸. The output result can be seen in wavelength spectrum of 400 nm-1200 nm. As a result, they noticed that reflectance was reduced to 30.2% to 2.37%, short circuit current density enhanced to 38.6 mA/cm², V_{OC} and FF were achieved to be 0.68V and 0.84. They concluded that there was an improvement in the wavelength of 700 nm by fixing the thickness of MgF₂ as 0.7(λ/4) and TiO₂ as 0.78(λ/4).

Sharma, Rajinder performed the numerical calculations in order to obtain reflectance from Si₃N₄ as SLARC and DLARC using transfer matrix method (TMM)¹⁹. For single film the transfer matrix is as:

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

η is tilted optical admittance with component represented by:

$$\eta_{\perp} = \sqrt{E_0/\mu_0 n \cos \theta}, \text{ for the perpendicular component.}$$

$$\eta_{\parallel} = (\sqrt{E_0/\mu_0 n} / \cos \theta), \text{ for the parallel component.}$$

θ is the propagation angle through the film.

$$\delta = \frac{(2\pi n_1 d_1 \cos \theta_1)}{\lambda_0} \text{ is the phase thickness of the film.}$$

d₁ is the thickness of layer while θ₁ is the diffraction angle.

For double layered the transfer function become:

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

This gives reflectance coefficients and reflectance as:

$$r = \frac{\eta_0 m_{11} + \eta_0 \eta_s m_{12} - m_{21} - \eta_s m_{22}}{\eta_0 m_{11} + \eta_0 \eta_s m_{12} + m_{21} + \eta_s m_{22}}$$

$$R = |r|^2$$

Where m₁₁, m₁₂, m₂₁, m₂₂ the elements of characteristics matrix are while η₀, η_s are the admittance values for medium and substrate.

PCID simulator was used to investigate the reflectance of silicon solar cell. They found that reflectance reduced from >30% to <2% having a short circuit current of 3.86 mA/cm². They noticed efficiency of 19.6% for single layered ARC and

20.22% for double layered ARC. Furthermore, $\text{Si}_3\text{N}_4/\text{Si}_3\text{N}_4$ as DLARC causes in reduction of reflectance to about <10% for the broadband range of 400-1100 nm and <2% for wavelength range of 500-900 nm.

Shah, Deb Kumar, et al. created DLARC using Zinc oxide (ZnO) and silver doped ZnO material on crystalline silicon solar cell using sol-gel method which is followed by annealing at 50 °C for 4 hours²⁰. They noticed considerable decrease in reflectance to about 7.13% in the broad band spectrum of 400 nm -1000 nm and it showed good surface property. So Ag doped ZnO could be promising DLARC on silicon solar cell with low cost.

4. Multiple Layered ARC

Sahouane et al. used MATLAB simulation to combine $n_1 = \text{SiN}_x$:H-rich silicon, $n_2 = \text{Silicon oxide}(\text{SiO}_x)$ and $n_3 = \text{oxynitride}(\text{SiO}_x\text{N}_y)$ to see the behavior of effective reflectivity (R_{eff}) for broadband range of 300-1100 nm as shown in Fig. 5²¹. They used transfer matrix method to implement optical equations to compute results. They also calculated IQE using Silvaco and PCID software. Table 2 shows the confirmation of minimum reflectivity when SiN_x :H combined with DLARC. The computed results also depict that multilayer comprising silicon nitride, silicon oxide and silicon oxynitride induces a valuable enhancement in photo generated current of 1.6 mA.cm⁻² compared to single layer ARC. Moreover the use of SiN_x :H having $d_3 > 30$ and $n_3 = 2.4$ can act as a good passivation and bulk layer.

Multi-layered coatings comprising of SnO_2 , Ta_2O_5 , ATO, TiO_2 , SiO_2 , and ITO have been prepared through Sol-Gel Dip

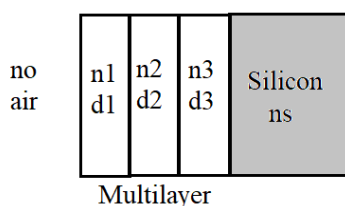


Fig. 5. Three layered structure

Table 2. Effective reflectivity by varying the layers

Cells (non-encapsulated)	n_1, d_1 (SiO_x)	n_2, d_2 (SiO_xN_y)	n_3, d_3 ($\text{SiO}_x\text{:H}$)	R_{eff} (%)
No ARC				34.5
Single layer			2.03 (73 nm)	11.7
Double layer		1.5 (55 nm)	2.1 (53 nm)	7.4
Triple layer	1.48 (80 nm)	2 (5 nm)	2.4 (50 nm)	4.4

coating technique²². Achieved coated films were characterized by XRD, SEM, ellipsometry and AFM. Single layered porous silica gave light transmittance of 95%. In multilayer films, after examine the relation between transmission of light and wavelength, it is found that ITO- TiO_2 - SiO_2 films and SnO_2 - Ta_2O_5 - SiO_2 films gave greater light transmittance of 97.5 % and 96.2 % which is higher as compared to SL SiO_2 film in the region around 300-900 nm wavelength. Thickness values of films are in the range of 30-115 nm.

Priyadarshini et al. concluded that thickness of multilayer coating plays an important part in decreasing the reflection from glass surface²³. They proposed three coating materials SiO_2 - TiO_2 -ZnO arranged such that SiO_2 is the first layer and ZnO is the third layer. The total thickness of all three layers fixed to about 206 nm. They described that if thickness of material obeys quarter-quarter-quarter (Q-Q-Q) and quarter-half-quarter (Q-H-Q) wavelength rule then there will be drastic decrease in reflectance spectra. This is due to fact that TiO_2 have higher RI then that of first and third layer and it showed the reflectance of 0.5 - 2% in the wavelength range of 400 -700 nm. They also gave good results of reflectance and transmittance if the incident angle varies from 0 to 90°.

Salih, Ammar et al. revealed that multi-layered Zinc Sulfide (ZnS) is a favorable and little cost ARC material for applications related to solar cells²⁴. In this research, they successfully deposited thin films of ZnS on a glass substrate with the use of a thermal evaporation technique containing three different layers of ZnS. AFM discloses the average grain size and roughness drop with quantity of layers. The reflectivity of Single, double and triple layered ZnS was calculated to be 0.105, 0.095 and 0.080. The optimal outcome was establish in three layered ZnS thin film having RI of 1.79 and comparatively little reflectivity of about 0.080 having broad band gap of 3.697 eV.

5. Conclusion

ARC is one of the important parameter to enhance the efficiency of PV module. The increasing demand of efficient solar panel makes the researchers to explore the best ways to improve light traction. This review paper has given the investigation about ARC, which can be well suited with silicon solar cell and glass substrate in order to reduce reflection. Many researchers proved experimentally the performance of material and their impact in enhancing the transmittance in wide range of wavelength spectrum. It is concluded that multilayer ARC have

more impact on decreasing the reflectance within the spectrum range as compared to single layered ARC and it is highly dependent on adjusting the thickness of film and RI of material.

Acknowledgments

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