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Effect of Single and Double Layer Antireflection Coating to Enhance Photovoltaic Efficiency of Silicon Solar

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The aim of this work is to investigate the effect of anti-reflection coating to improve the performance of silicon solar cell. The reflectance for different anti-reflection coating materials (SLARC and DLARC) were calculated numerically as well as on online source of PV Education. The parameters of such materials are used in PC1D simulator to study the performance of solar cells. It was found that DLARC has considerable effect on the performance of solar cell as compare to SLARC. Further, it was observed that the photovoltaic efficiency and short circuit current is significantly high for SiO_2/TiO_2 DLARC.

Keywords: Antireflection coating, SLARC, DLARC, Efficiency, PC1D.

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1. INTRODUCTION

World's most of the electricity was produced from fossil fuel such as coal, oil and natural gas etc. The increasing demand of electric energy and scarcity of fossil fuel force the people to think about the alternate ways to produce electric energy and solar energy is one. Solar cell is a promising approach for terrestrial and space photovoltaic devices. But the main challenge regarding the performance of solar cell is the reflection losses. When sunlight illuminate the front surface of solar cell, some part of light energy transmitted into the cell and get converted into electrical energy whereas some part reflects from the front surface. In order, to reduce the loss due to reflectance on silicon surface different methods have been used. Light trapping, surface texturing and anti-reflection coatings (ARC) etc are most widely used methods to reduce the loss due to reflection [1-4].

The reflectivity of bare silicon surface is quit high i.e. more than 30 % of incident light get reflect from silicon surface [7-9]. Thus ARCs are of great importance to improve the efficiency of solar cell by reducing the loss due to reflection [6-10]. The ARCs containing single layer can be non-reflective only at single wavelength, generally at the mid of visible spectrum where as ARCs containing double layer are effective over the whole visible spectrum. Various materials have been used as ARCs in silicon solar cell e.g. MgF_2, SiO_x, Si_xN_x, Al_2O_3, Ta_2O_5, TiO_2 and ZnS.

In this work an attempt has been made to investigate effect of MgF_2, SiO_2, Si_3N_4, Al2O3, TiO_2 and ZnS layers (SLARC) and their binary combinations (DLARC) on the bare silicon surface.

2. THEORY OF ANTIREFLECTION COATING

Most of the solar cells are coated with anti-reflection coating layer to reduce reflection of light on the front surface of cell [5]. A set of optimized and well designed anti-reflection coating on front surface reduce the reflectivity on the front surface of cell from 30 % down to less than 5 % [4]. Fig. 1 shows the principle of "Interference of light in thin film". The light reflected from interface ***a*** and ***b*** interferes destructively and hence transfers their energy to the cell.

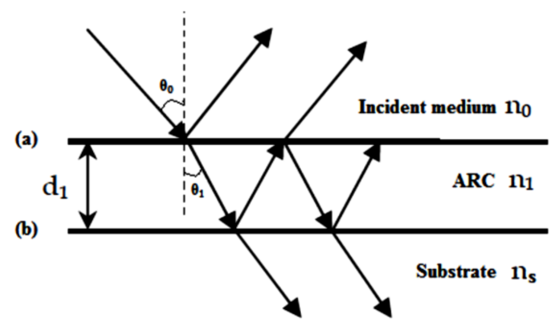

Fig. 1 – Reflection at the interface between two media

The expression for reflected energy, when the incident light strike normally on silicon surface covered with transparent layer of thickness d_1, is given by [11, 12]

$$R = \frac{r_1^2+r_2^2+2r_1r_2cos2\theta}{1+r_1^2r_2^2+2r_1r_2cos2\theta} \quad (1)$$

Where, $r_1 = \frac{n_0-n_1}{n_0+n_1}$, $r_2 = \frac{n_1-n_2}{n_1+n_2}$ and $\theta = \frac{2\pi n_1 d_1}{\lambda_0}$. When, $n_1 d_1 = \frac{\lambda_0}{4}$ is satisfied, the reflectivity become minimum i.e. $R_{min} = \left[\frac{n_1^2-n_0n_2}{n_1^2+n_0n_2}\right]^2$.

Thus for the transparent layer with zero reflectance (i.e. $R = 0$),

$$n_1 = \sqrt{n_0 n_2} \quad (2)$$

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which gives refractive index of anti-reflection film of desired wavelength λ_0. Anti-Reflecting materials used and their refractive indexes are listed in Table 1. But for the incident light with wavelength different from λ_0, reflectivity will increase. So, in order to increase the output of solar cell, the distribution of solar spectrum and relative spectral response of silicon should be taken into account and reasonable wavelength will be chosen. The peak energy among solar spectrum occur at 0.5 μm, whereas the peak of relative spectrum response of silicon cell is in the range of 0.8-0.9 μm wavelength, so the wavelength range of best anti-reflection is in 0.5-0.7 μm [12].

Table 1 – AR-coating material with their refractive index [12].

S. No.	Material	Refractive Index
1	MgF_2	1.38
2	SiO_2	1.46
3	Al_2O_3	1.76
4	Si_3N_4	2.00
5	ZnS	2.36
6	TiO_2	2.62

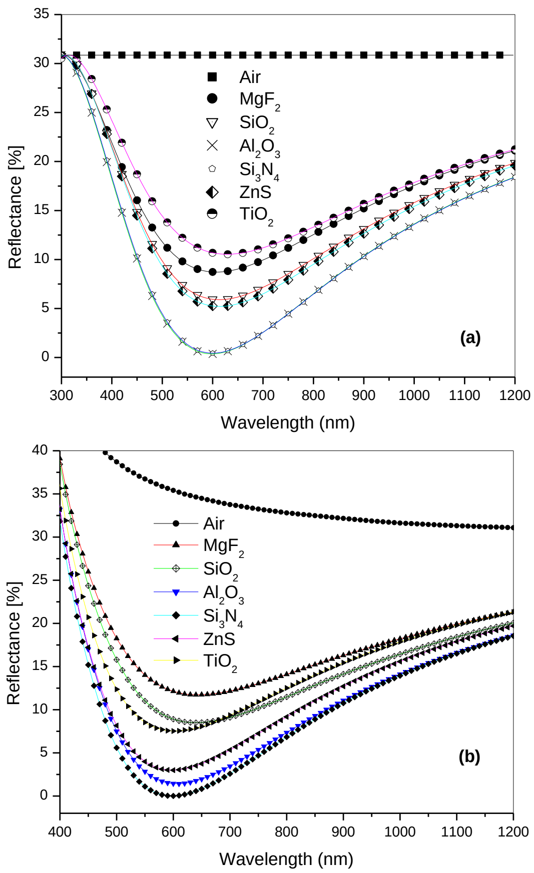

Fig. 2 – Variation of reflectance as a function of wavelength for bare Si and with SLARC. (a) using eq. (1) and (b) obtained from PC1D

A further reduction in reflectivity is achieved through double layer anti-reflection coating (DLARC). For double layer anti-reflection coating, the expression of reflectance is more complicated and is expressed as [11]

$$R = \frac{A+B+C+D+E+F}{1+(r_1^2 r_2^2)+(r_1^2 r_3^2)+(r_2^2 r_3^2)+C+D+E+F} \quad (3)$$

Where, $A = (r_1^2 + r_2^2 + r_3^2)$, $B = (r_1^2 r_2^2 r_3^2)$, $C = 2r_1 r_2(1 + r_3^2)cos2\theta_1$,

$$D = 2r_2 r_3(1 + r_1^2)cos2\theta_2,$$
$$E = 2r_1 r_3 cos2(\theta_1 + \theta_2),$$
$$F = 2r_1 r_2^2 r_3 \cos(\theta_1 - \theta_2),$$

$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$, $r_2 = \frac{n_1 - n_2}{n_1 + n_2}$, $r_3 = \frac{n_2 - n_3}{n_2 + n_3}$, $\theta_1 = \frac{2\pi n_1 d_1}{\lambda_0}$ and $\theta_2 = \frac{2\pi n_2 d_2}{\lambda_0}$.

3. RESULT AND DISCUSSIONS

Fig. 2 (a) shows the variation of reflectance as a function of wavelength for bare silicon and coated with different ARC layers under normal incidence. The reflectance for bare silicon as well as coated with ARC layers of MgF_2, SiO_2, Al_2O_3, Si_3N_4, ZnS and TiO_2, for the quarter-wavelength thickness of 110, 105, 85, 75, 65 and 60 nm are calculated by using eq. (1).

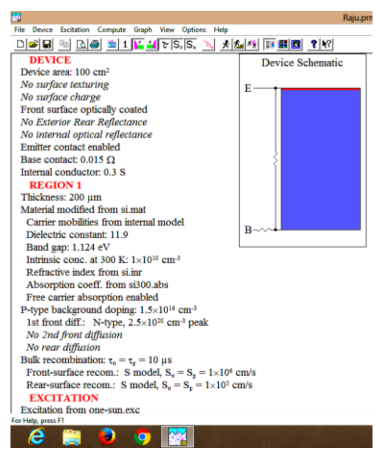

Fig. 3 – Summary of simulation parameters for PC1D Model

From Fig. 2 (a), it is observed the reflectance of bare silicon is high (> 30%), whereas reflectance with SLARCs is < 20 % for wavelength longer than 500 nm and the value of reflectance become < 0.4 % for $n = 1.76$ (Al_2O_3) & 2.00 (Si_3N_4) at wavelength 600 nm. Plot also shows, the reflectance is minimum only at one wavelength and is high for other than this wavelength. The increase in reflectance is gradual on higher wavelength side and is sharp on low wavelength side.

Graph-2 (a) shows a good agreement between curves obtained using eq. (1) - symbols and from PV Education source – solid lines. Further, the above conditions (i.e. without and with SLARC) are used in PC1D program to study the performance of silicon solar cell. PC1D based simulation model of silicon solar cell is shown in Fig. 3. Fig. 2(b) shows the reflectance curves of the silicon solar cell with and without ARCs. According to this figure, the ARC layer help to reduce reflectance considerably which

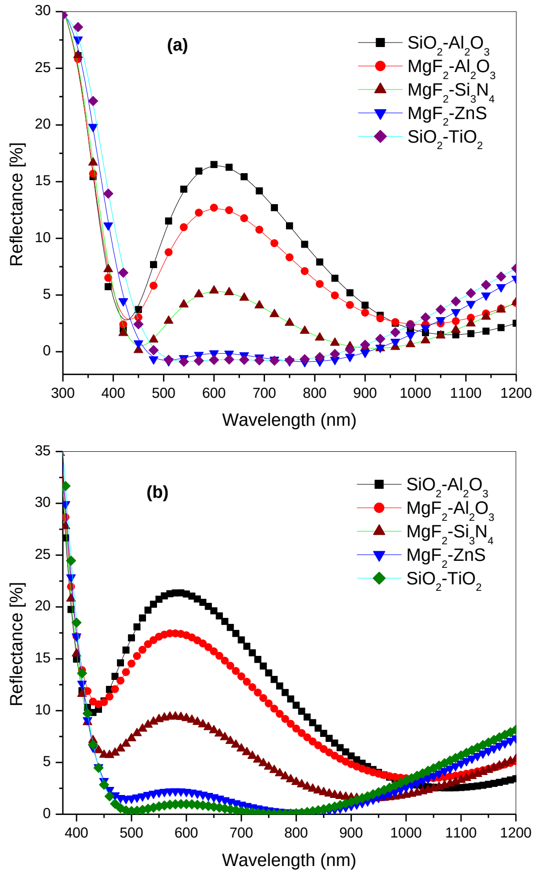

Fig. 4 – Variation of reflectance as a function of wavelength for silicon solar cell with DLARC. (a) using equation (3) and (b) from PC1D

in turn increase the short circuit current (Table-2) due to increase in the absorption of photons from incident light. It is observed from Table 2, the efficiency of silicon solar cell without ARC is 9.3 % where as it become 13.6 % with Si_3N_4.

In order to reduce reflectance further over wide range of wavelengths, double layer anti-reflection coating (DLARC) were considered. Fig. 4 shows the variation of reflectance as a function of wavelength. Here, we calculated the reflectance for different binary combinations of ARCs by using eq. (3). The reflectivity curve for DLARC is W – shaped that means reflectivity reaches to minimum value corresponding to two wavelengths, which contribute to reduce reflectivity over wide range of wavelength (400-1200 nm). From fig. 4, it is clear that the effect of DLARC is much better as compare to SLARC. According to figure the reflectance for MgF_2/ZnS and SiO_2/TiO_2 DLARC over wavelength rang 450-900 nm is almost negligible.

Thus, it is expected that the performance of solar cell would be much better by using DLARC in the wavelength range of 450-900 nm of solar energy. Similar to SLARC, the performance of the solar cells with DLARC were evaluated using PC1D. Results so obtained are presented in Fig. 4(b), Fig. 5, Fig. 6 and Table 2. The results of simulation show the performance of solar cell get improved

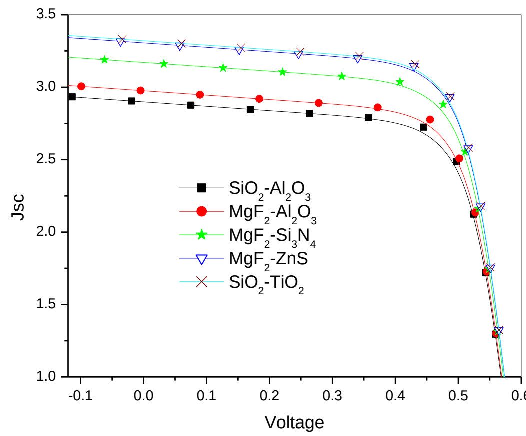

Fig. 5 – *I-V* curves of solar cell with DARCs

Table 2 – Photovoltaic data of silicon solar cells with SLARC and DLARC under AM 1.5 irradiation (PC1D)

ARC	I_{sc}(A)	V_{oc}	FF	η (%)
Air	2.18	0.587	0.726	09.3
MgF_2	2.83	0.594	0.722	12.2
SiO_2	2.90	0.595	0.714	12.4
Al_2O_3	3.11	0.597	0.723	13.4
Si_3N_4	3.15	0.597	0.724	13.6
ZnS	3.06	0.597	0.723	13.2
TiO_2	2.94	0.595	0.714	12.5
SiO_2/Al_2O_3	2.90	0.595	0.716	12.36
MgF_2/Al_2O_3	2.96	0.596	0.709	12.57
MgF_2/Si_3N_4	3.17	0.597	0.724	13.71
MgF_2/ZnS	3.31	0.599	0.721	14.28
SiO_2/TiO_2	3.32	0.599	0.721	14.34

considerably with the use of DLARC on front surface of cell. For a batter comparison, the parameters such as I_{sc}, V_{oc}, FF and η, for different ARC layers are presented in Table 2.

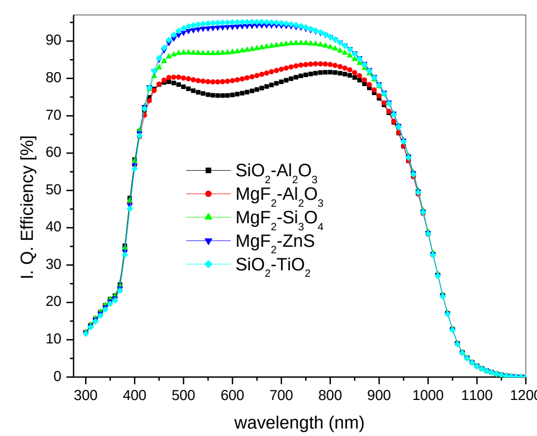

Fig. 6 – Variation of internal quantum efficiency as a function of wavelength of light

Fig. 4(b) shows, the reflectance with MgF_2/ZnS and SiO_2/TiO_2 is almost negligible over a wide range of wavelength (450-900 nm). As a result there is increase in the internal quantum efficiency (Fig. 6) as well as in the short circuit current (Fig. 5). From Fig. 6, it absorbed the internal quantum efficiency for DLARCs MgF_2/ZnS and SiO_2/TiO_2 is > 95 % in the wavelength range from 450-900 nm where as short circuit current is increased by a 52 % approximately. From Table 2 it is also observed that the efficiency of silicon solar cell become 14.28 % and 14.34 % for MgF_2/ZnS and SiO_2/TiO_2 respectively.

4. CONCLUSION

Effect of SLARC and DLARC were investigated theoretically to improve the performance of silicon solar cell. Application of SLARC on front surface improve the performance of solar cell partially, however, a properly designed DLARC improve the performance to a large extent. Results show that low weighted reflectance can be achieved by applying SiO_2/TiO_2 DLARC with an increase in I_{sc} from 2.18 to 3.32 along with photovoltaic efficiency of about 14.34 %.

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