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Selection of Materials for Double Layer Antireflection Coating of Silicon Solar Cell

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ABSTRACT

In present work an attempt has been made to select material to design double layer antireflection coatings (DLARC) for silicon solar cell, theoretically. In this regard, silicon nitride (Si_3N_4) is used along with MgF_2 and SiO_2 to design DLARC to achieve zero reflectance over wide range of spectra. Reflection spectra for DLARC systems of MgF_2/Si_3N_4 and SiO_2/Si_3N_4 have been evaluated numerically using transfer matrix method (TMM). Further, reflectance for MgF_2/Si_3N_4 is investigated at various monitoring wavelengths (λ_o = 550, 600, 650 and 700 nm). Calculated reflectance has been used in PC1D simulator to study the effect of double layer antireflection coating on optical and electrical parameters of silicon solar cell. Simulation results shows, reduction in reflectance form > 30% down to zero in the wavelength range 500 – 700 nm with conversion efficiency 21.33% at 600 nm for MgF_2/Si_3N_4.

Key words: ARC,silicon nitride, PC1D, silicon solar cell, reflectance, conversion efficiency

1.INTRODUCTION

Solar energy is the conversion of sunlight into electric energy by solar cell. The performance of a solar cell depends on the amount of light energy absorbed by the material of solar cell. The main challenge regarding the performance of solar cell is the loss of light energy due to reflection from front surface of solar cell. For bare silicon reflectivity is quite high i.e., more than 30% of incident light reflects from the silicon surface [1]. Different methods used to reduce reflection loss are surface texturing, light trapping, and antireflection coating etc [2, 3].Thus, antireflection coating (ARC) plays very important role to improve the conversion efficiency of solar cell.

An ideal antireflection coating system on solar cell surface can reduce reflection loss to zero over a wide spectral range. Single layer antireflection coating (SLARC) can be non-reflective only at single wavelength, generally at the mid of visible spectrum where as double layer antireflection coatings (DLARC) are effective over wide range of visible spectrum [2].Antireflection coating is a thin layer of dielectric materials. Various dielectric materials are available to form single, double, and multi-layer ARCs. The reflectivity depends on refractive index, thickness, substrate, wavelength, and angle of incidence etc. So, one must pay due attention to select perfect ratio of refractive indices while designing DLARC for minimum reflection. There have been many reports on antireflection coatings in recent past. Effect of single and double-layer ARCs of different materials are investigated by R. Sharma et al. [2], SiO_2/TiO_2 by Lien et al. [4], Al_2O_3/TiO_2 by Bahrami et al. [5], $MgF_2/Ti_2O_3$by M. Medhat et al. [6]and Si_3N_4/Si_3N_4 by R. Sharma [7].

In this work an attempt has been made to design and investigate double layer antireflection coating (DLARC) for silicon solar cell by using MgF_2 and SiO_2on $Si_3N_4$to achieve zero reflectance over wide range of spectra. Si_3N_4 has been selected as material for inner layer of ARC because its refractive index can be varied from 1.8 –3.0 by varying deposition parameters and it exhibit good surface passivation quality for refractive index above 2.3 [7, 8].

2. DLARC MODELING

Conversion efficiency of solar cell can be improved considerably by applying a good antireflection coating. A set of well-designed double layer antireflection coatings (DLARC) on front surface can reduce the reflectivity of solar cell from 30% down to zero [2]. Transfer matrix is commonly used method to calculate the reflectivity of ARCsas this relates the tangential components of electric and magnetic fields across the boundary of layers [6, 7, 9, 10].Thus, transfer matrix for DLARC under normal incidence can be expressed as [6-11]:

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

where $\delta_{(1,2)} = \frac{2\pi n_{(1,2)} d_{(1,2)} \cos\theta_{(1,2)}}{\lambda_o}$ is phase thickness of film, $d_{(1,2)}$ is the thickness of film, $\theta_{(1,2)}$ 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 [7, 11]

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

where $Y = C/B$, therefore reflectance for assembly of double layer coating and substrate ($air/n_1/n_2/n_s$) can be expressed as:

$$R = \frac{\left[(n_0 - n_s)cos\delta_1 cos\delta_2 + \left(\frac{n_1 n_s}{n_2} - \frac{n_0 n_s}{n_1}\right) sin\delta_1 sin\delta_2\right]^2 + \left[\left(\frac{n_0 n_s}{n_2} - n_2\right) cos\delta_1 sin\delta_2 + \left(\frac{n_0 n_s}{n_1} - n_1\right) sin\delta_1 cos\delta_2\right]^2}{\left[(n_0 + n_s)cos\delta_1 cos\delta_2 - \left(\frac{n_1 n_s}{n_2} + \frac{n_0 n_s}{n_1}\right) sin\delta_1 sin\delta_2\right]^2 + \left[\left(\frac{n_0 n_s}{n_2} + n_2\right) cos\delta_1 sin\delta_2 + \left(\frac{n_0 n_s}{n_1} + n_1\right) sin\delta_1 cos\delta_2\right]^2} \quad (3)$$

For good ARC, reflectance must be reduced to zero i.e. $R = 0$. Minimum reflectance can be achieved by choosing the ARC layers and substrate that satisfies the following condition.

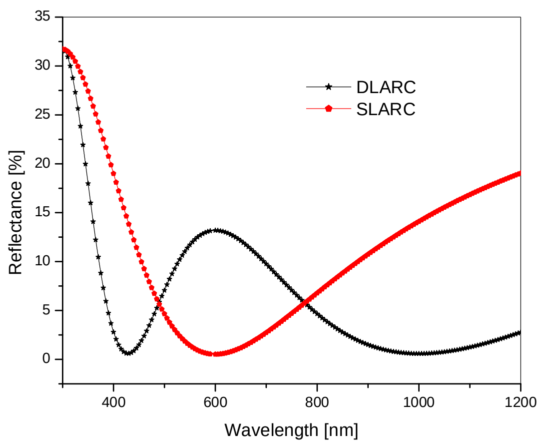

Figure 1: Plot shows variation of reflectance for SLARC (Al_2O_2) and DLARC (MgF_2-ZnS) as a function of wavelength.

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

Above condition determine the materials required for DLARC. Available materials that satisfy above condition nearly are $MgF_2$and TiO_2[6].

Here it is proposed that one can design DLARC using silicon nitride (Si_3N_4) for inner layer (n_2), as its refractive index can be varied from 1.8 to 3.0 [7-9].In this way one can obtain two or more DLARCs in place of single (MgF_2/TiO_2) with zero reflectance. In present work two DLARC systems, MgF_2/Si_3N_4 and SiO_2/Si_3N_4that satisfy eq. (4) are under consideration.

3.DEVICE SIMULATION

Simulation plays a vital role both to improve the existing devices as well as to develop new one. In the field of PV technology, numerical modeling is increasingly used to obtain insight into the electrical and optical properties. 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.

Table-1: Parameters used in PC1D to calculate electrical and optical parameters of 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 1.5,100 W/cm^2)
Layer Parameters	
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}
Front-surface recombination velocity	10^4 cm/s
Rear-surface recombination velocity	10^4 cm/s

In present work PC1D simulator is used to simulate and study silicon solar cell. PC1D simulator consist two files i.e. "**one-sun.exe**" and "**scan-qe.exe**" that contain standard parameters used to study electrical and optical parameters of solar cell. This program also accepts the reflectance as an external file, which provides opportunity to include desired reflectance [7, 10, 12]. Table - 1 shows list of input parameters used to calculate electrical parameters of silicon solar cell using PC1D simulator.

4.RESULTS AND DISCUSSION

4.1 REFLECTANCE

Figure 1 shows the variation of reflectance as a function of wavelength for SLARC and DLARC. From figure one can find the reflectivity curve for SLARC is V-shaped that is reflection is minimum at single wavelength only. Whereas for DLARC reflectivity curve is W-shaped that is reflectance become minimum at two wavelengths. Depending on the values of n_1 and n_2, reflectance curve for DLARC can be reduced from W-shape to U-shape over wide range of spectra. Detail of ARC layers such as refractive index and layer thickness are shown in Table 2. Variation of reflectance as a function of wavelength for MgF_2/Si_3N_4 and SiO_2/Si_3N_4 of quarter-wavelength thickness under normal incidence as a function of wavelength are shown in figure 2.

From figure one can observe that: (a) reflectance curves for MgF_2/Si_3N_4 and SiO_2/Si_3N_4 are overlapped i.e. reflection due to both DLARCs is same, (b) reflectance for both ARC systems (MgF_2/Si_3N_4 and SiO_2/Si_3N_4) have been reduce to zero in wavelength range 500 - 750 nm.

Table 2: Refractive index (eq. 4) and thickness (at λ_o = 600 nm) of ARC materials used for simulation.

S. No	Layers	μ	d (nm)
1	MgF_2/Si_3N_4	1.38/2.61	108.7/57.5
2	SiO_2/Si_3N_4	1.42/2.69	105.6/55.8

Further, to study the effect of monitoring wavelength (λ_o), coatings for MgF_2/Si_3N_4 have been designed (using TMM) to hold minimum reflection for the monitoring wavelength (λ_o) at 550, 600, 650 and 700 nm.

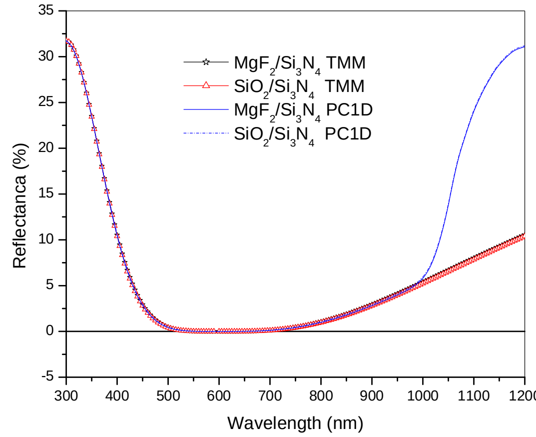

Figure2: Variation of reflectance as a function of wavelength.

These calculated reflectances have been used in PC1D simulator to study the performance of silicon solar cell. Figure 3 show a good agreement between numerically calculated reflectance and obtained from PC1D for monitoring wavelength (λ_o) at 550, 600, 650 and 700 nm.

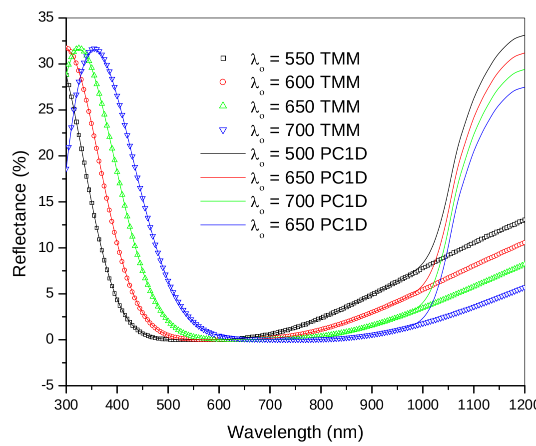

Figure 3: Plot showing variation of reflectance as a function of wavelength at various monitoring wavelengths (λ_o) for MgF_2/Si_3N_4.

From figure one can observe that the minimum reflectance shifted toward higher wavelength side with increase in monitoring wavelength (λ_o) as well as there is considerable increase in the range of minimum reflectance with the increase in monitoring wavelength (λ_o) i.e. 450 – 700 nm at λ_o = 550 nm, 500 – 800 nm at λ_o = 600 nm, 550 – 900 nm at λ_o = 650 nm and 575 – 975 nm at λ_o = 700 nm for MgF_2/Si_3N_4 ARC System. Detail analysis (Figures 2-5 & Table 3) shows the performance of silicon solar cell is good at λ_o = 600 nm for DLARCs under consideration.

4.2 EXTERNAL QUANTUM EFFICIENCY

Quantum efficiency is an important parameter of solar cell and is defined as the ratio of number of photons collected by solar cell to number of photons incident on it. In a solar cell, quantum efficiency relates electrical parameters (like short circuit current and conversion efficiency) with optical parameters (reflectance) [6, 7]. A good ARC is one which promises high performance of solar cell by decreasing reflection and increasing photocurrent. Thus, the performance of ARC can be analyzed in terms of reflectance and EQE i.e. for zero reflectance, EQE will be 100% [6, 7]. EQE curves as a function of wavelength for cells without ARC, with zero reflectance and with DLRCs at different monitoring wavelengths are shown in figure 4. Graph shows EQE curve for DLARC at λ_o = 600 nm is in good agreement with zero reflectance over wide range of spectra.

4.3 ELECTRICAL PARAMETER

On theaccount of improvement in the optical parameters (reflectance & quantum efficiency), good improvement in electrical parameters is expected. I-V characteristics curves of the solar cell without ARC, with DLARCs and one with zero reflectance are shown in Figure 5. Plot shows a significant increase in the short circuit currents with DLARC layer and is almost close to short circuit current due to zero reflectance.The short circuit current, open circuit voltage, fill factor and photovoltaic efficiency of the silicon solar cell corresponding to various monitoring wavelengths (λ_o) for MgF_2/Si_3N_4 have been presented in Table 3.

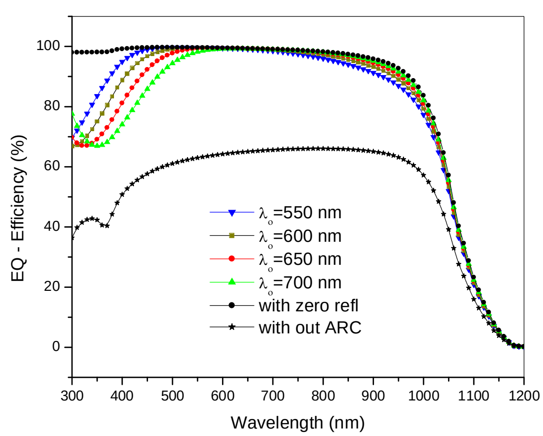

Figure 4: Plot shows variation of external quantum efficiency as a function of wavelength for MgF_2/Si_3N_4.

Table 3: Photovoltaic data of silicon solar cell with DLARC (MgF_2/Si_3N_4) under AM 1.5 irradiation (PC1D).

λ_o (nm)	J_{sc} (mA/cm^2)	V_{oc} (volt)	FF (%)	η (%)
550	39.51	0.68	79.73	21.27
600	39.62	0.68	79.74	21.33
650	39.51	0.68	79.73	21.27
700	39.22	0.67	79.70	21.09

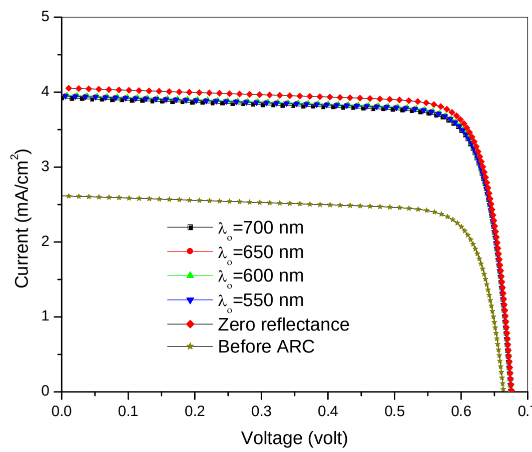

Figure 5: Current – voltage characteristics of silicon solar cell at various monitoring wavelengths for MgF_2/Si_3N_4 DLARC system.

5.CONCLUSION

In present work this has been demonstrated that due to varying refractive index (1.8 – 3.0) and high passivation quality,silicon nitride (Si_3N_4) can be usedin combination with MgF_2 and SiO_2 to design to design DLARCs with zero reflectance for silicon solar cell. Further, this is observed, the zero reflectance of these DLARCs over wide range of solar spectra (550 – 900 nm) at monitoring wavelength (λ_o= 600 nm) produce quantum efficiency identical to ideal silicon solar celland exhibit good performance.

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