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Comparison of refractive index graded Antireflection Coating on Silicon Substrate for Solar cell Application

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***Abstract*- Present work aims at the characterization of ARC films in the visible spectrum, up to five layers antireflection coating film were designed and simulated, optical reflection values were deduced with a Transfer Matrix Method formulation (TMM). Six materials including nanoporous material have been selected to investigate the optimum values of the Anti reflection coating (ARC) film for solar cells. The present work has been carried out to investigate the optimum values of reflectance as a function of wavelength in the visible region. The reflectance has been reduced from 32% of silicon surface to less than 1% using multilayer ARC film. It has been observed that by increasing the number of layers the average reflectance decreases over a broad range of visible spectrum.**

Keyword: Antireflection Coating (ARC), Reflectance, Transfer Matrix Method, Double layer, Three Layer, Four Layer, Five Layer, Solar cells.

1. Introduction

Silicon is the best known semiconductor optical material with relatively high refractive index. The most important application of silicon in the visible spectrum is photovoltaic solar panel [Berning, 1963; Dobrowolski, 1995]. The conversion of solar energy into other energy form is more effective if the reflectance of the light receiving surface of solar device is minimal in the solar spectrum range [Kolton, 1981]. The efficiency of a solar cell and its lifetime can be raised by coating the light sensitive surface of the cell with an Anti Reflection Coating (ARC) [Kolton, 1981]. To obtain the AR response at a single wavelength, a single layer or two layers are sufficient. However, when the AR function is broadened to cover a range of wavelengths, the number of layers must also be increased, and the AR structure is a multilayer structure. Many design procedures have been applied to solve this design problem. Most of these procedures address the problem of having a fixed number of refractive indices that are repeated periodically. The optimal length of each layer that satisfies the required specifications is then determined [Kumar et al., 2005; Macleod, 2001]. The matrix method [Mussett et al., 1970] is usually employed for calculation of the reflection coefficient. While the well-known single layer quarter-wave film can lead to zero reflection at a single wavelength, broadband ARC is often needed for many applications. In practice coating materials with the required refractive index for the quarter-wave antireflective (AR) film may not be available. To address these issues, a multilayer stack of homogeneous thin films has been investigated extensively for over half a century [Schallenberg, 2008], resulting in the development of a rich variety of multilayer thin film schemes [Thelen, 1989] and design methodologies [Wright D.N. et al., 2005]. The aim of this research is to present a computational process for the numerical design and simulation of antireflection coatings. The optical thickness and refractive index of each layer is adjusted to optimize the reflectance as a function of wavelength.

2. Design Methodology

Transfer Matrix Method is used to calculate the reflection coefficient of a multilayer stack, which consist of series of k thin film dielectric layers, having a physical thickness $d_1,d_2,d_3,\ldots\ldots,d_k$ and refractive indices $n_1,n_2,n_3,\ldots\ldots n_k$, respectively, deposited on a substrate of refractive index n_s. Then for normal indices of light, the reflection (R) and transmission (T) of such a stack is given by the following expression:

$$R = \left(\frac{1 - Y}{1 + Y}\right)^2 \qquad (1)$$

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And $T = 1 - R$. (These expressions are true for an absorption-free multilayer stack.) Where $Y = C/B$ is known as optical admittance of the stack, and

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (2)$$

Where $$\begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix} = \prod_{r=1}^{K} \begin{bmatrix} \cos\delta_r(\lambda) & \frac{i\sin}{\eta_r}\delta_r(\lambda) \\ i\eta_r \sin\delta_r(\lambda) & \cos\delta_r(\lambda) \end{bmatrix} \quad (3)$$

The phase thickness of the rth layer is given by $(\delta_r(\lambda) = (2\pi\eta_r d_r)/\lambda)$ for the normal incidence of light of wavelength λ. For symmetrical multilayer stack $M_{11} = M_{22}$, and if $M_{11} \neq M_{22}$ the multilayer is called an unsymmetrical multilayer stack. The matrix involved in the equation (3) is called characteristics matrix and its determinant is unity [Kumar et al., 2005; Macleod, 2001]. The process of finding the R, T involves essentially computation of the optical admittance Y of the stack by matrix multiplication method provide that refractive index as a function of λ and the physical thickness of each layer is known. Therefore, the necessary and sufficient conditions to produce zero reflectance are calculated based on equations 4-7 [Schallenberg, 2008].

For a double layer

$$n_1^4 = n_0^3\, n_{si} \quad ; \quad n_2^4 = n_0\, n_{si}^3 \quad (4)$$

For a three layer

$$n_1^8 = n_0^7\, n_{si} \;; n_2^8 = n_0^4\ n_{si}^4 \;\; ; \; n_3^8 = n_0\ n_s^7 \quad (5)$$

For a four layer

$$n_1^{16} = n_0^{15}\, n_{si} \; ; \; n_2^{16} = n_0^{11}\ n_{si}^5 \; ; \; n_3^{16} = n_0^5\ n_{si}^{11} \; ; \; n_4^{16} = n_0 n_{si}^{15} \quad (6)$$

For a five layer

$$n_1^{32} = n_0^{31}\, n_{si} \;\; ; \; n_2^{32} = n_0^{26}\ n_{si}^6 \;\; ; \; n_3^{32} = n_0^{16}\ n_{si}^{16} \;\; ; \; n_4^{32} = n_0^6\ n_{si}^{26} \;\; ; \; n_4^{32} = n_0\ n_{si}^{31} \quad (7)$$

3. Reflectance Spectrum Analysis

The simulation of the reflection in Matlab has been the main assignment of this work, the reflectivity of the silicon has been simulated with two, three, four and five layers of antireflection coatings. The program is optimized at λ_0 = 633 nm central wavelength for visible spectral region. As it has been demonstrated by many researchers that optical thin film materials with refractive index as low as 1.05 can also be created, therefore as per equation (6) and (7) refractive index is calculated and found to be 1.17 as this has been taken for analysis based on nanoporous Silicon dioxide (SiO_2), Indium Tinoxide (ITO), Titanium Dioxide (TiO_2) and we have precisely controlled porousity by using oblique angle deposition technique [Schubert, 2012].

3.1. Double Layer Antireflection Coating

The refractive index n_{si} of silicon in the spectral region 400-700 nm is 3.5 and when the surrounding medium is air (n_0=*1*) the refractive index of the first layer should be 2.5 and of the second layer should be 1.3 so the two different combinations of dielectric materials (Silicon Dioxide with Zinc Sulphide) and (Magnesium Fluoride with Cerium Oxide) were selected as given in figure 1. The reflectance spectra of double layer coating of the above two combinations of dielectric materials, with varying optical thickness were analyzed.

Normal Incidence of Light ↓	Normal Incidence of Light ↓
$n_1(1.5)$	$n_1(1.4)$
$n_2(2.4)$	$n_2(2.5)$
$n_s(3.5)$	$n_s(3.5)$

Figure 1. Schematic of double layer, optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light.

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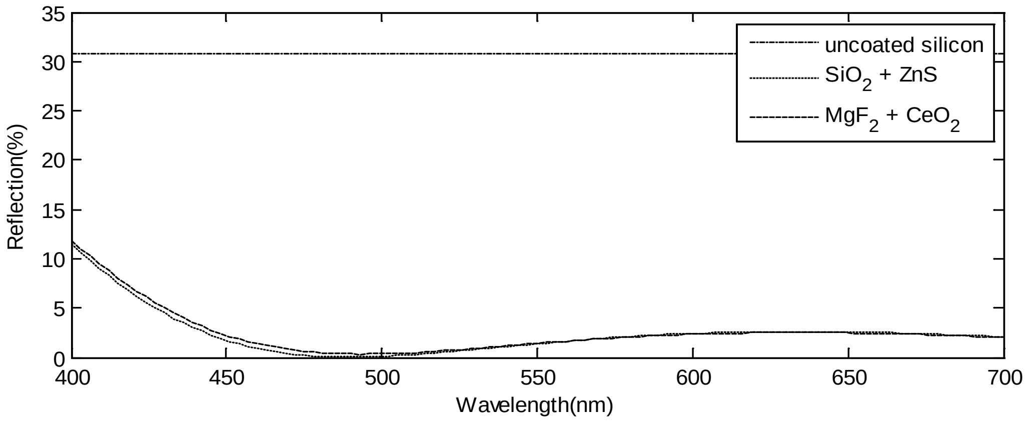


Figure 2. Reflectance spectra of Double layer antireflection coating on silicon.

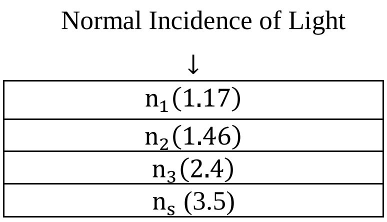
Figure 2 shows a comparison of reflectance of two different (dual layer) ARC films with that of without ARC film. In figure 2, the reflectance graph of both ARC films of quarter-quarter optical thickness is shown. As per the graph, Silicon Dioxide with Zinc Sulphide has shown almost zero reflection point and lower average reflectance. A minimum reflectance of 0.01% is achieved at 490 nm. This layer has reduced the average reflection from 32% to 2.34% in between 400-700 nm. This has the form of broadband ARC film which may be suitable for use in antireflection film on silicon solar cells. The simulated results of minimum and average reflectance of double layer ARC films are tabulated in table 1.

Table 1. Reflectance of double layer ARC films

Thickness/Length	Types of ARC Film	Wave Length(nm)	Minimum Reflectance (%)	Avg. Reflectance (%)
λ/4 & λ/4	SiO_2 +ZnS	490	0.01	2.34
	MgF_2 + CeO_2	493	0.32	2.23

3.2. Three Layer Antireflection Coating

Here three layer antireflection coating is considered for simulation. Figure 3 gives schematic of three layers of optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light. In figure 4, the reflectance graph of two ARC films of quarter-quarter-quarter optical thickness is shown. The layer consisting of nanoporous material with Silicon Dioxide and Titanium Dioxide has shown better performance in the range of 400-700nm as its average reflectance is very low at 1.48%. This has the form of broadband ARC film which may be suitable for use in antireflection film on silicon solar cells. The layer of Magnesium Fluoride, Cerium Fluoride and Zirconium Dioxide has shown almost zero reflectance (0.0025%) at 634nm. As this layer has a minimum reflectance at 634 nm it may be suitable for Helium Neon lasers applications and as an ARC film in the upper wavelength band of visible spectrum. The simulated results of minimum and average reflectance of three layer ARC films are tabulated in table 2.



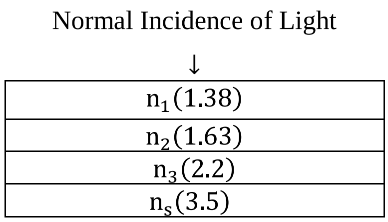


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Figure 3. Schematic of three layers, optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light.

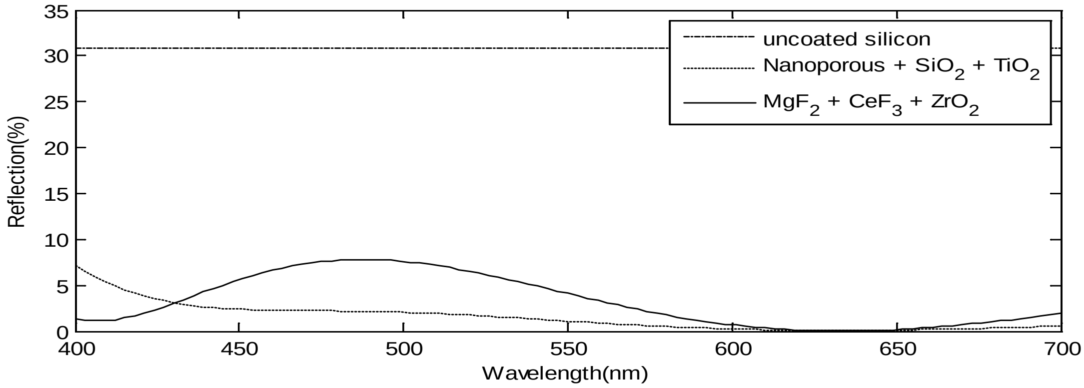

Figure 4. Reflectance spectra of Triple layer antireflection coating on silicon.

Table 2. Reflectance of triple layer ARC films

Thickness/Length	Types of ARC Film	Wave Length (nm)	Minimum Reflectance (%)	Avg. Reflectance (%)
λ/4 & λ/4 & λ/4	Nanoporous $+SiO_2+TiO_2$	634	0.076	1.48
	$MgF_2+CeF_3+ZrO_2$	634	0.0025	3.20

3.3. Four Layer Antireflection Coating

Figure 5 shows schematic of four layers of optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light. In figure 6, the reflectance graph two ARC films for the quarter-quarter-quarter-quarter optical thickness is shown. As per the graph, Nanoporous material, Silicon Dioxide, Cerium Fluoride and Titanium Dioxide layer has shown a lower value of average reflectance of 2.04% throughout the visible spectrum, which may be suitable for use in antireflection film on silicon solar cells. It is also good for the optoelectronic devices which operate in the visible spectrum. It can be seen from the figure that if Cerium fluoride is replaced by Magnesium Fluoride, the ARC film shows 2.17% minimum reflectance at 634nm. This form of ARC film can be suitable for use in Helium Neon lasers. The simulated results of minimum and average reflectance of four layer ARC films are tabulated in table 3.

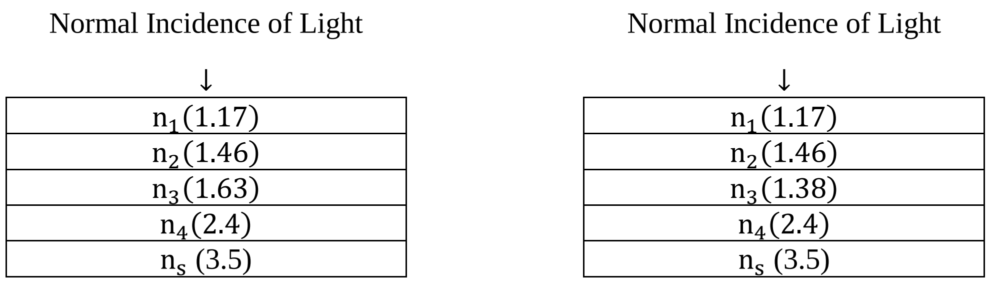

Figure 5. Schematic of four layers, optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light.

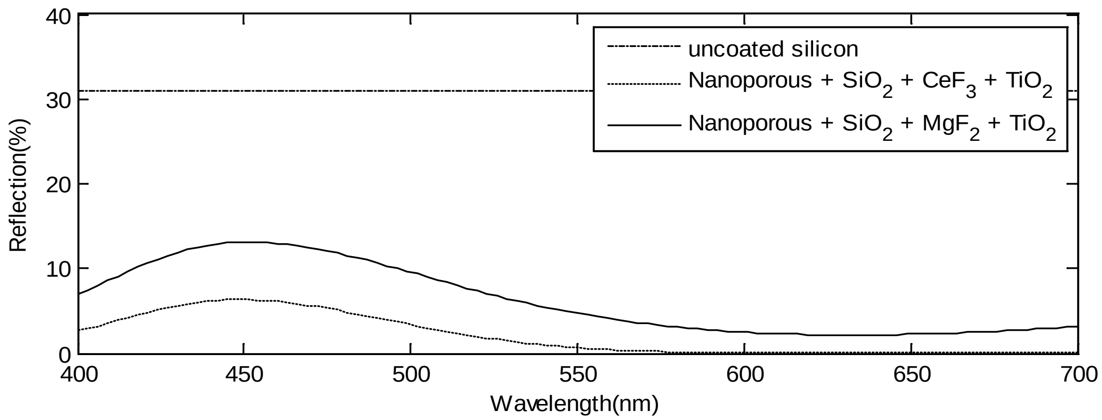

Figure 6. Reflectance spectra of four layer antireflection coating on silicon

Table 3. Reflectance of four layer ARC films

Thickness/Length	Types of ARC Film	Wave Length (nm)	Minimum Reflectance (%)	Avg. Reflectance (%)
λ/4 & λ/4 & λ/4 & λ/4	Nanoporous+SiO_2+CeF_3+TiO_2	634	0.032	2.04
	Nanoporous+ SiO_2+MgF_2+TiO_2	634	2.17	6.3

3.4. *Five Layer Antireflection Coating*

Now finally the five layer ARC has been considered as shown in figure 7, which shows the schematic having optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light. It can be seen in figure 8 that by addition of a fifth layer of low index and selecting the Low High Low High formation of outer four layers and the fifth layer of index close to that of substrate, a five layer ARC of nanoporous, Silicon Dioxide, nanoporous, Silicon Dioxide and Titanium Dioxide is formed. The graph depicts that the broadening effect is achieved and as a result an average reflectance of 6.28% is achieved in the visible region (400-700 nm). The other formation of nanoporous, Silicon Dioxide, Magnesium Fluoride, Cerium Fluoride and Titanium Dioxide has almost zero average reflectance in the higher range of visible spectrum (500-700nm) and this type of ARC film may be suitable for narrowband (500-700nm) optoelectronic devices and not for the solar cell applications in the visible spectrum. The simulated results of minimum and average reflectance of five layer ARC films are tabulated in table 4.

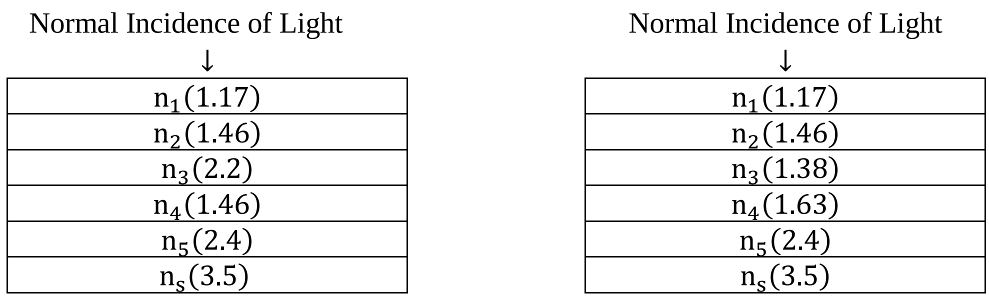

Figure 7. Schematic of five layers, optical thickness $n_1 d_1$ and wavelength λ_0 for normal incidence of light.

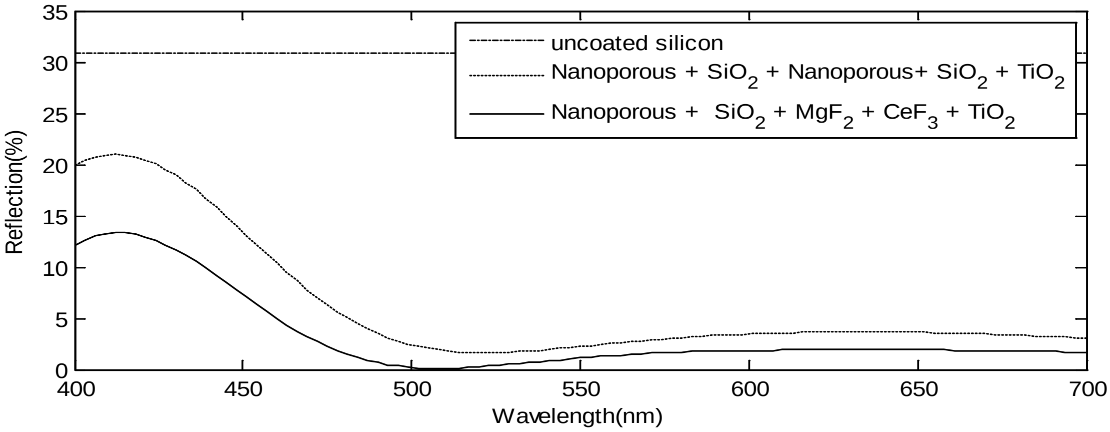

Figure 8. Reflectance spectra of five layer antireflection coating on silicon.

Table 4. Reflectance of five layer ARC films

Thickness/Length	Types of ARC Film	Wave Length(nm)	Minimum Reflectance (%)	Avg. Reflectance (%)
λ/4 & λ/4 & λ/4 & λ/4 & λ/4	Nanoporous+SiO_2+ Nanoporous+SiO_2+TiO_2	520	1.61	6.28
	Nanoporous+SiO_2+ MgF_2+CeF_3 +TiO_2	508	0.0945	3.36

4. Conclusion

The surface of silicon reflects huge part of the incident light radiation in the whole spectral range between 400-700 nm as its refractive index is relatively high. A double layer can be a better solution of antireflection coating in the range between 400-700 nm. But double layer ARC does not minimize this high reflectance over a broad range of wavelength although it reduces reflection drastically compared to a plain silicon surface. The three layer ARC consisting of nanoporous material with Silicon Dioxide and Titanium Dioxide has shown better performance in the broad range of 400-700nm as its average reflectance is very low at 1.48%. The Four layer ARC of Nanoporous material, Silicon Dioxide, Magnesium Fluoride and Titanium Dioxide has shown a better performance with 2.17% minimum reflectance at 634nm and may be suitable for use in Helium Neon lasers. The Five layer ARC of nanoporous, Silicon Dioxide, Magnesium Fluoride, Cerium Fluoride and Titanium Dioxide has almost zero average reflectance in the higher range of visible spectrum (500-700nm) and this type of ARC film may be suitable for narrowband (500-700nm) optoelectronic devices.

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