Broadband and Wide Angle Antireflection Coatings for Solar Cell Applications

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Abstract:

Design and evaluation of a broadband and wide angle antireflection coating (AR) for solar cell can operate at incident angles of 0^0-70^0 and over a wavelength range of 400-1200 nm were studied in details in this paper. The antireflection system consists of two layers of MgF_2 and TiO_2 in the form: Air/ MgF_2, TiO_2/ Si. The target reflection spectrum at any incident angle must be minimum for whole range of wavelength (400-1200 nm). The designs are based on the optical thin film theory, with the aid of an optimization method. The results indicate that the AR coatings thicknesses that give minimum reflection are function of incident angles. Also the error in reflectance spectrum increased with the increase in incident angle. It is obvious that the thickness of MgF_2 material is more influence by angle of light incident than TiO_2 material thickness which is approximately a constant thickness.

Keywords: Solar cell, Antireflection coating, Optical thin film.

Introduction

Antireflection (AR) coatings are used extensively in a wide variety of optical systems to reduce unwanted reflections. AR coatings for solar cells are particularly important, because the reducing of reflection at the surface of solar cells directly will increases efficiency. Conventional AR coatings for solar cells consist of single-layer quarter wave transparent films that provide excellent AR characteristics at the designed wavelength for normal incidence. However, performance of such quarter-wave coatings falls off when deviating from normal incidence or the designed wavelength. Because sunlight is broadband and its angle of incidence changes throughout the day, broadband and omnidirectional AR characteristics are highly desirable for solar cell devices [1, 2].

A solar cell converts absorbed photons into electrical charges. Ideally, it should absorb all useful photons. However, more than 30% of incident light is reflected back from the surface of the silicon solar cells because of the high refractive index of silicon material. Antireflection coatings are therefore widely utilized to improve the conversion efficiencies of Si solar cells [3].

An ideal antireflection structure should lead to zero reflection loss on solar cell surfaces over an extended solar spectral range for all angles of incidence. Therefore, the development of a perfect broadband and wide angle antireflection structure has been an important issue in solar cell applications [3, 4].

In this paper, a design of broadband and wide angle antireflection can operate at incident angles of 0^0-70^0 and over a wavelength range of 400-1200 nm. The designs are based on the optical thin film theory, with the aid of an optimization method.

1. Theoretical work

The theory of antireflection coatings has been widely discussed in the reference [5]. The silicon material spectrum response range is 400–1200 nm. Considering solar spectrum distribution, the antireflection should operate at an 800 nm spectral range. In this range, the coating materials have an appreciable dispersion that cannot be neglected and have to be handled properly throughout the whole design process. The high- and low-index materials are TiO_2 and MgF_2. The refractive indices used in the calculations are given in Table (1) [6]. As shown in Table (1), the Si material refractive index is very high. In this situation, a solar cell will have high residual reflection if it has no antireflection.

The internal quantum efficiency (IQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy shining on the solar cell. IQE therefore relates to the spectral response of a solar cell, it is given as a function of either wavelength or energy. The internal quantum efficiency ideally has a square shape with constant values across the entire spectrum of wavelengths measured. However, the IQE for most solar cells is reduced because of the effects of recombination. Figure (1) shows the basic graph of the quantum efficiency for the silicon solar cell used for the calculations of this research [7].

Table (1): The refractive indices of the used materials [6]

Wavelength (nm)	Refractive index		
	Si	MgF_2	TiO_2
400	5.1099	1.3903	2.5440
500	4.2583	1.3850	2.3570
600	3.9647	1.3800	2.2890
700	3.9133	1.3768	2.2620
800	3.8687	1.3762	2.2500
900	3.8124	1.3756	2.2495
1000	3.7677	1.3750	2.2490
1100	3.7123	1.3745	2.2485
1200	3.6775	1.3740	2.2480

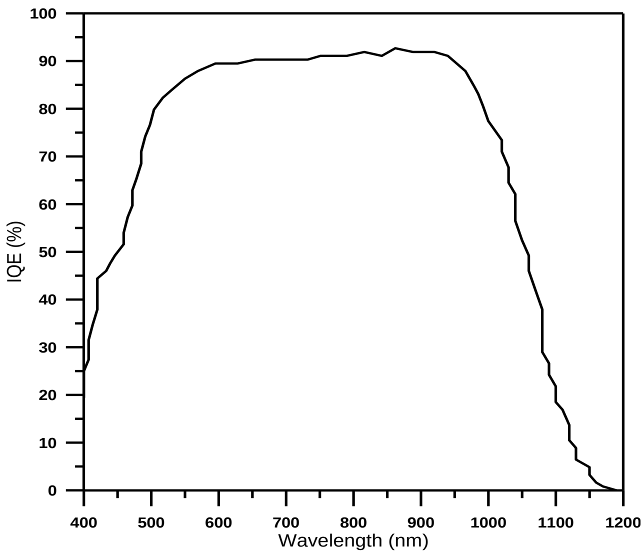

Figure (1): Internal quantum efficiency curves for screen printed silicon solar cell [7].

The weighted reflectance (eq. 1) or transmittance (eq. 2) is the real values of reflectance or transmittance under the effect of the internal quantum efficiency [6, 7]:

$$R_{weighted} = \frac{\sum_i IQE(\lambda_i).R(\lambda_i,\theta_i)}{\sum_i IQE(\lambda_i)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$T_{weighted} = \frac{\sum_i IQE(\lambda_i).T(\lambda_i,\theta_i)}{\sum_i IQE(\lambda_i)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$R(\lambda_i,\theta_i), T(\lambda_i,\theta_i)$ are the reflectance and transmittance at any incident angle. $IQE(\lambda_i)$ is the internal quantum efficiency. ($R_{weighted}$, $T_{weighted}$) are the values of reflectance and transmittance with the effect of the internal quantum efficiency.

2. Theoretical results

The antireflection system consists of two layers of MgF_2 and TiO_2 in the form: Air/ MgF_2, TiO_2/ Si. The target reflection spectrum at any incident angle must be zero for whole range of wavelength (400-1200 nm), unfortunately this demand cannot be achieved. Using multilayer equations and optimization technique, one can find minimum reflectance spectrum for any incident angle. The optimization technique will find the antireflection coating layers thicknesses that can achieve minimum reflectance for the whole wavelength range and for possible incident angles. Table (2) shows the thicknesses of the materials required for different incident angles. It is obvious that the AR coatings thicknesses that give minimum reflection are a function of incident angles. Also table (2) indicates that the error in reflectance spectrum increased with the increase in incident angle. Since the thickness of MgF2 is higher than that of TiO2 so the thickness of MgF_2 material is more influence by angle of light incident than TiO_2 material thickness which is approximately a constant thickness as shown in Figure (2).

Table (2): The designing layers thicknesses with respect to light incident angle.

Incident Angle degree	Thickness nm		Mean error Reflectance %
	MgF_2	TiO_2	
0	109.07	64.69	3.633
10	109.95	64.87	3.640
20	112.95	65.41	3.690
30	119.35	66.31	3.878
40	132.37	67.62	4.330
50	158.31	69.39	5.054
60	189.31	72.29	6.093
70	214.81	73.81	10.457
80	238.23	72.53	28.569

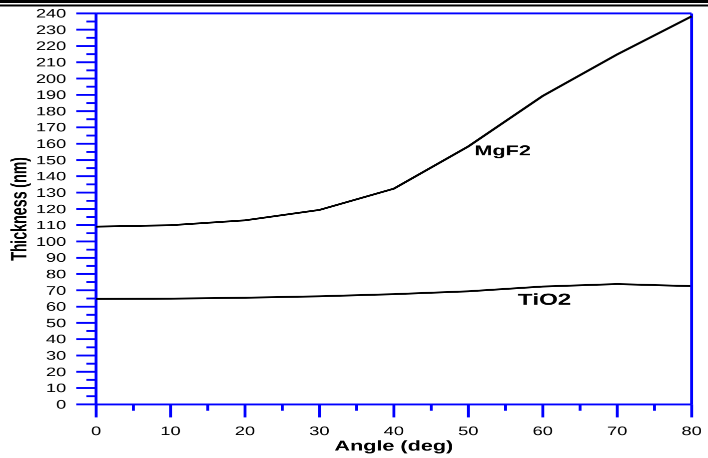

Figure (2): The antireflection coatings thicknesses for different light incident angles.

The problem of choosing best thicknesses for both antireflection materials can be achieved by using the optimization condition:

$$\sum_{\lambda,\theta} R(\lambda,\theta) = minimum \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3)$$

$R(\lambda,\theta)$ is the reflectance as a function for both wavelength and incident angle. The resulting thicknesses according to optimization condition are (158.31, 69.39 nm) for MgF_2 and TiO_2, respectively.

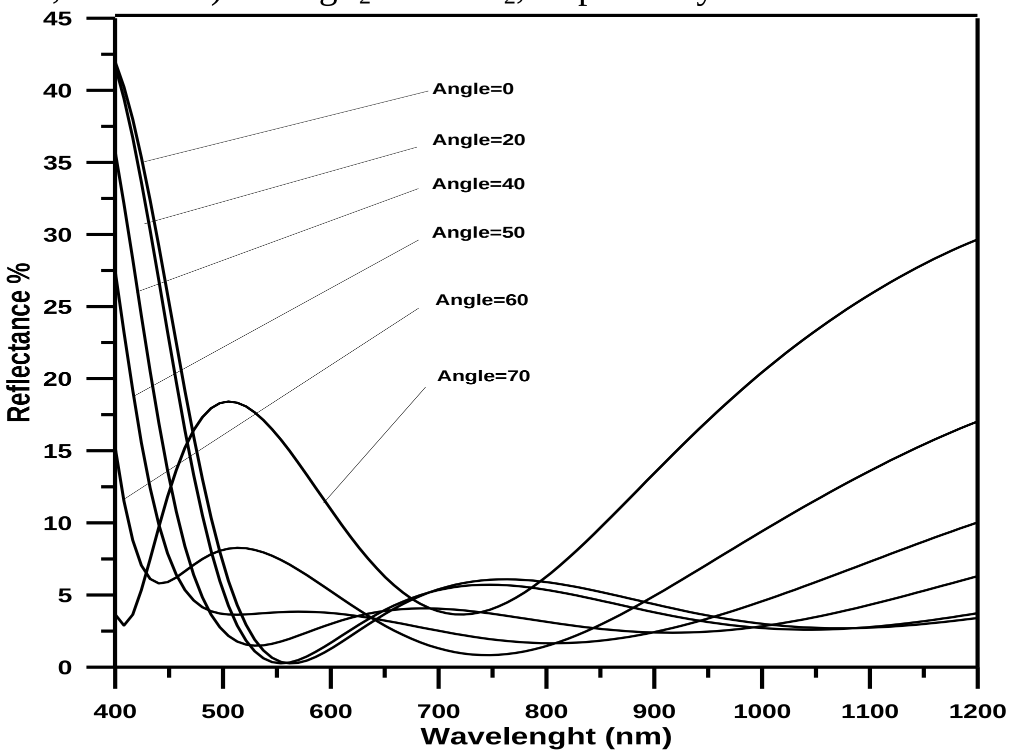

Figure (3): Reflectance with wavelength for various incident angles.

Figure (3) show that the reflectance at the effective range of wavelengths (550-950 nm) is about 5 % for incident angle less than 70^{o} .

Figure (4) which represents the weighted reflectance values for all range of wavelength illustrate that the transmittance over (92%) for incident angle less than 60^o.

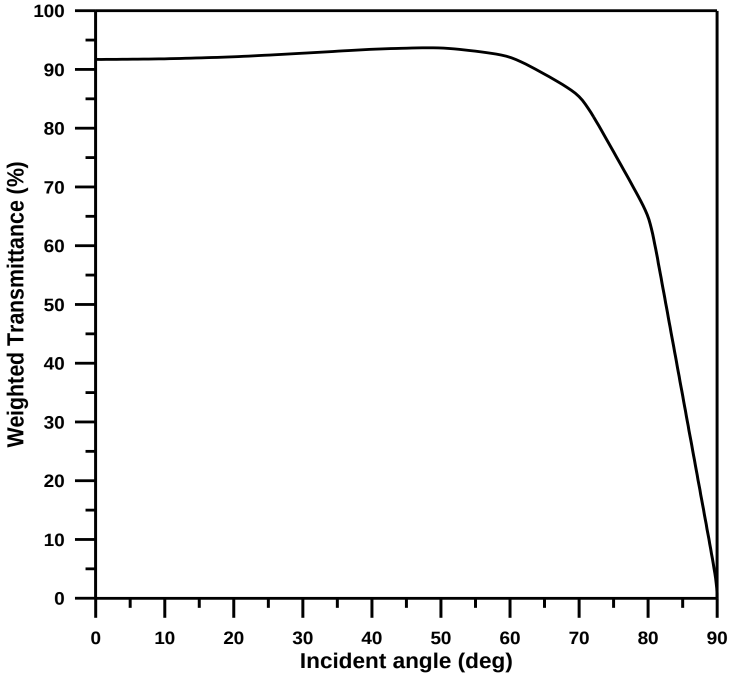

Figure (4), The weighted transmittance versus the incident angles.

The weighted transmittance depends on the sum of the internal quantum efficiency and the transmittance for all range of wavelengths (for any incident angle) as shown at equation (2). It can be seen due to figures (1 and 3) for wavelength region (300-500 nm), the transmittance has high values while the internal efficiency has low values, also for the wavelength region (500-1000 nm), the transmittance and the internal efficiency have medium values, for both cases the weighted transmittance has approximately constant values, but for wavelength region greater than (1000 nm) the internal efficiency drops to zero making the weighted transmittance tends to zero too.

Conclusions

The antireflection system consists of two layers of MgF_2 and TiO_2 in the form: Air/ MgF_2, TiO_2/ Si. The target reflection spectrum at any incident angle must be minimum for whole range of wavelength (400-1200 nm), unfortunately this demand cannot be achieved. Using multilayer equations and optimization technique, one can find minimum reflectance spectrum (maximum transmittance spectrum) for any incident angle. From the optimum results one concludes that the reflectance for all incident angles is high for wavelength less than (500 nm) and more than wavelength

(950 nm). While the reflectance at the effective range of wavelengths (550-950 nm) is about 5 % for incident angle less than 70^{o} by using the optimization thicknesses (158.31, 69.39 nm) for MgF_2 and TiO_2, respectively.

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طلاء مضاد للانعكاسية ذو مدى زاوي و موجي واسع لتطبيقات الخلايا الشمسية

الخلاصة

ان تصميم طلاء مضاد للانعكاسية ذو مدى زاوي و موجي واسع يعمل ضمن زوايا سقوط الاشعاع 0–70 درجة ولطول موجي ضمن المدى 400–1200 نانومتر قد تمت دراسته ضمن هذا البحث. الطلاء يتكون من طبقتين مؤلفة من مادتي (MgF_2 و TiO_2) بالشكل (هواء/ MgF_2 / TiO_2 / سليكون) . ان طيف الانعكاسية الذي يجب الحصول عليه يجب ان يكون اقل ما يمكن لكل المدى الموجي المطلوب. ان التصميم مبني على اساس نظرية الاغشية الرقيقة وباستخدام مبدأ النهايات الصغرى. اوضحت النتائج ان سمك مادتي الطلاء الذي يحقق اقل انعكاسية يكون دالة لزوايا سقوط الاشعاع.كما ان الخطأ في طيف الانعكاسية وازدياد قيمته يعتمد على زيادة زاوية السقوط. كما تم اثبات ان سمك مادة ثاني فلوريد المغنيسيوم مؤثرة بشكل اكبر من سمك مادة ثاني اوكسيد التيتانيوم على منحني طيف الانعكاسية وبالتالي على زوايا السقوط...حيث يبقى سمك ثاني اوكسيد التيتانيوم ثابت تقريبا.