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Simulation of Anti-Reflective TiO_2/SiO_2 Coating for Silicon Photovoltaic Application by Ray Tracing

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ABSTRACT

In solar systems, anti-reflective coatings are used to reduce reflection and increase efficiency. However, the front surface on the solar cells alone is not effective because most of the light from the sun is reflected and very less energy absorption into the solar cells occur. An anti-reflective coating (ARC) of a sufficient thickness can greatly reduce front surface reflectance. Nanoscale surface texturing, on the other hand, can efficiently capture a higher ratio of incident light to boost optical absorption. In this study, the light trapping scheme within the wavelength of 300 to 1200 nm was used to improve the overall efficiency of silicon solar cells. A thin layer of TiO_2 *and* SiO_2 *anti-reflective coating with different thicknesses was stacked alternatingly due to their different refractive index with* TiO_2 *having a high refractive index and* SiO_2 *with a low refractive index. Solar irradiance spectrum AM1.5G at normal incidence was used in this present work. For the ray-tracing simulation, the front planar with multilayer ARC with different thicknesses were investigated to obtain the optimum value for optical properties and current density. All the four combination arrangements of* SiO_2 *and* TiO_2 *were evaluated and the maximum potential photocurrent density (Jmax) was calculated. The Jmax value of thin crystalline silicon, c-Si (without ARC) was 24.93* mA/cm^2 *and increased to 30.28* mA/cm^2 *when ARC was used on the front surface. This represents an increasing of 21.46 % enhancement compared to the Jmax of the c-Si reference.*

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Keywords: Solar cell; TiO_2/SiO_2*; Anti-reflection coating (ARC); current density.*

INTRODUCTION

Ray tracing of the solar cell was established a decade ago however ray tracing of an entire module has met difficulties. This is mainly because geometric structures with a very large scale of dimensions are affecting the module optics [1]. Currently, researchers are developing various ways to increase the efficiency of actual solar cells by including nano micro-structuration of the surface, using absorbing nanoparticles, and the use of anti-reflective coating, ARC [2]. It is undeniable that using anti-reflective coating gives a major improvement in solar cell efficiency [3]. The anti-reflective coating can be made using several methods such as electron beam (e-beam) evaporation, magnetron sputtering, chemical vapor decomposition, and the sol-gel process. The sol-gel process is the most favourable in making anti-reflective coating because of its benefits in high production, low cost, and easy process and it is essential to constitute coating with an adjustable refractive index [4]. The application of thin films of SiO_2 and TiO_2 using the sol-gel process was utilized as an anti-reflective coating on monocrystalline silicon wafers [5]. By controlling the coating thickness and the refractive index of an anti-reflective coating, minimum reflectance can be achieved [4].

Due to the high refractive index of Si (3.8), Si solar cells suffer from considerable optical losses of roughly 35 % in general. Si solar cells have optical losses that limit their ability to generate more electricity, lowering their overall power conversion efficiency [6]. Various technologies, including anti-reflection coatings, are being investigated to lower the optical losses associated with Si solar cells. The ARC acts as a refractive index match between air with a refractive index of 1 and the Si substrate with a refractive index of 3.8 [6]. TiO_2 film is frequently utilized as a high refractive index layer in multilayer AR films. In addition, for the low refractive index layer, SiO_2 with a refractive index of 1.46 at 550 nm is commonly utilized [7]. Wang et al. discovered that a TiO_2/SiO_2 bilayer coating raised the maximum transmittance of the glass substrate in the visible range from 88.5 to 92.3 percent [8]. Previous research shows SiO_2 and TiO_2 are very suitable to design anti-reflective films.

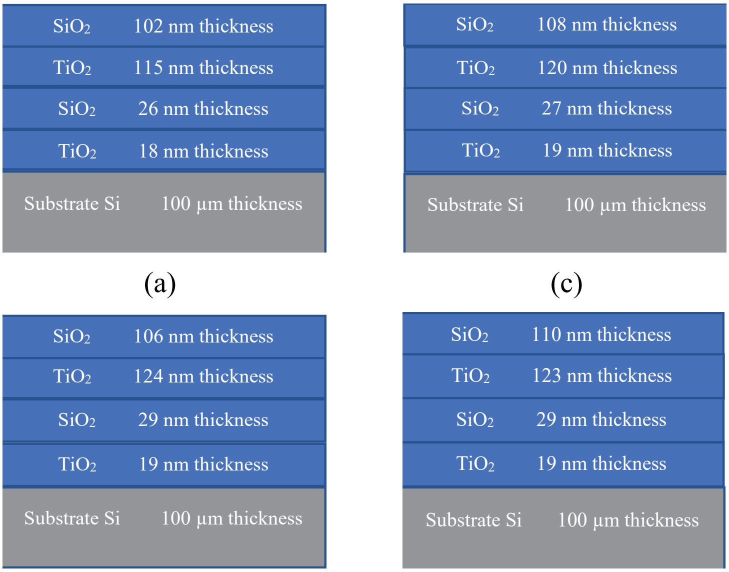
Ray tracing is the combination of Monte Carlo and thin-film optics to determine current density and optical losses under a given illumination spectrum. This ray tracing weighs the magnitudes of photogeneration and optical loss in a solar cell or test structure [9]. The photocurrent density in a wafer is equivalent to Jmax that could be gained from a perfect solar cell made from wafer. PV lighthouse simulation based on the wafer optics calculator integrates the influence of the wafer bulk and both of its surfaces. This simulation can estimate data of reflection, transmission, and thin-film absorption at a single surface and a powerful to simulate the optics of photovoltaic solar cells. Development of light trapping (LT) scheme using this simulation can be optimized ray tracing multiple times before the actual thin c-Si solar cells are fabricated. This help to reduce development costs and increase performance of solar cells [9].

Numerical simulations were used to build multi-layer ARC with improved optical properties [10]. Following that, multi-layer ARC films containing SiO_2 and TiO_2 were created in this study by simulation. Solar AM1.5G is used because it is a spectrum that includes the blue sky and the surrounding ground, which is called the global spectrum, hence named Solar AM1.5G. In this work, four LT scheme with multi-layer ARC of TiO_2 and SiO2 with different thicknesses is stacked alternatingly. From the absorption curve in the thin c-Si, maximum potential photocurrent density(Jmax) is calculated to observe performance of each schemes. The Jmax is calculated within 300-1200 nm wavelength region and the highest absorption from four LT scheme is compared for thin crystalline silicon (c-Si) solar cells with 100 μm thickness.

METHODOLOGY

In this paper, a broadband ARC on a silicon substrate was constructed with a single maximum in reflectance and a minimum number of layers, maximizing the amount of accessible light (primarily in the wavelength range of 400 to 700 nm) to improve the overall efficiency of the silicon solar cell. To simulate the reflectance, the input parameters are ARC on top of the silicon substrate. The light incidence angle was set at 90°, and the configuration of four alternating layers consisting of the substrate and the alternation of low refractive index material and high refractive index material with the first layer of ARC be the high refractive index material. SiO_2 (low refractive index, n = 1.45 at 600 nm), TiO_2 (high refractive index, n = 2.53 at 600 nm), and silicon substrate with 100 μm thickness were chosen for the simulation [10].

The layer diagram of the multi-layered ARC of SiO_2 and TiO_2 on a planar photovoltaic cell is illustrated in Figure 1. Thickness of layer diagram was arrange referring to Zambrano *et al*, [10]. All four combination arrangements are incremental which means the light absorption and Jmax value are expected to be higher across the schemes. The ARC was designed into an arrangement of low-high-low-high refractive index material.

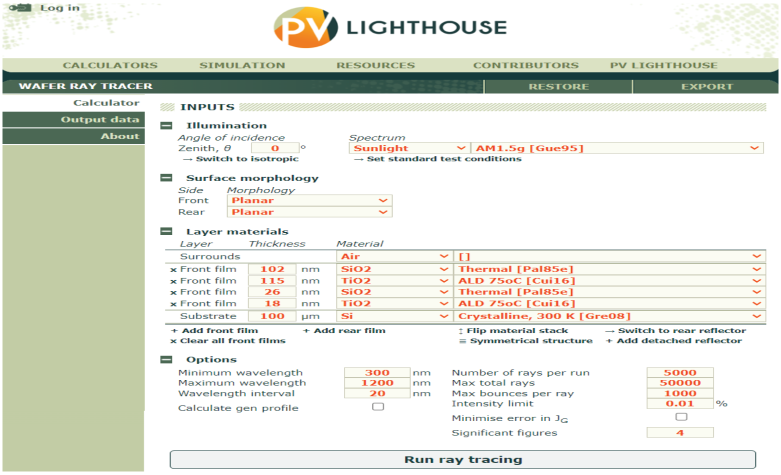


(a) (c)

(b) (d)

Figure 1: Layer diagram of multilayer ARC on Substrate Silicon with a constant thickness of 100 μm.

Figure 2 shows the simulation of PV lighthouse used in this study. This simulation enhanced by the Wafer Optics Calculator [11]. Through the website, the layer materials can be adjusted under a given illumination spectrum. This calculator calculates the photogenerated current density in a solar cell or test structure. The Wafer Optics Calculator integrates the influence of the wafer bulk and both of its surfaces, whereas it's precisely estimated reflection, transmission, and thin-film absorption at a single surface [9]. As a result, the Wafer Optics Calculator allows for the evaluation of all-optical losses and light trapping. In the wavelength range requested, the Wafer Optics Calculator calculates optical losses and photogeneration. The short circuit current that might be extracted from a perfect solar cell built from the wafer is equal to the photo-generated current Jg in the wafer. In PV Lighthouse AM1.5G was used at zero incident angle because it is normal to the surface of a solar cell. A maximum of 50,000 rays were used with 5,000 rays per run. The optical characteristics of solar cells are studied in the wavelength range of 300-1200 nm with a 20 nm interval [12]. The surface morphology was set to planar since this work is on the planar surface solar cell with different thicknesses of multi-layered ARC. The thickness and positions of the four ARCs were shown in the calculator as in Figure 2.



Illumination

Angle of incidence Zenith, θ: 0 °

Spectrum: Sunlight, AM1.5g [Gue95]

Surface morphology

Side	*Morphology*
Front	Planar
Rear	Planar

Layer materials

Layer	*Thickness*		*Material*	
Surrounds			Air	[]
x Front film	102	nm	SiO2	Thermal [Pal85e]
x Front film	115	nm	TiO2	ALD 75oC [Cui16]
x Front film	26	nm	SiO2	Thermal [Pal85e]
x Front film	18	nm	TiO2	ALD 75oC [Cui16]
Substrate	100	µm	Si	Crystalline, 300 K [Gre08]

Options

Minimum wavelength	300	nm	Number of rays per run	5000	
Maximum wavelength	1200	nm	Max total rays	50000	
Wavelength interval	20	nm	Max bounces per ray	1000	
Calculate gen profile	☐		Intensity limit	0.01	%
			Minimise error in J_G	☐	
			Significant figures	4	

Figure 2: PV Lighthouse Simulation

In the simulation, total reflection, transmission, and absorption in thin c-Si wafers of the incident light and Jmax are investigated and analysed. From the absorption results, the thin c-Si performance of the c-Si solar cell was assessed using J_{max} as shown in equation 1. J_{max} was calculated by integrating the absorption curve over the AM1.5G solar spectrum for wavelengths 300-1200 nm.

$$J_{max} = q \int EQE\ (\lambda).S(\lambda)\ d\lambda \qquad (1)$$

Where q is the electron charge and S(λ) is the standard spectral photon density of sunlight for AM1.5G spectrum. In this calculation, carrier collection is assumed to be unity (i.e. internal quantum efficiency, IQE=1). Enhancement of solar sell with multi-layer anti-reflective coating was calculated using the equation 2.

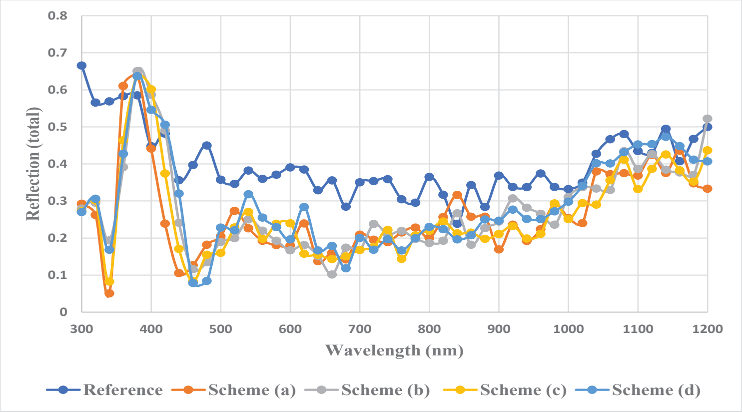
$$J_{\text{max}} \text{ enhancement } (\%) = \left[\frac{J_{\text{max scheme}} - J_{\text{max reference}}}{J_{\text{max reference}}}\right] \times 100\% \qquad (2)$$

RESULT AND DISCUSSION

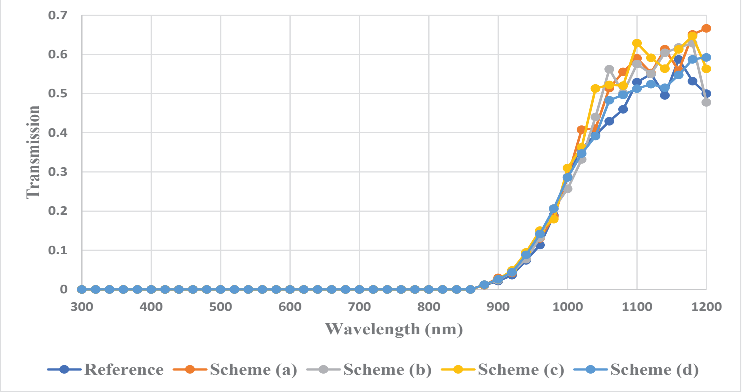
Figure 3 shows the reflection, absorption, and transmission curves of 100µm c-Si with different thickness of SiO_2 and TiO_2 multi-layered ARC as the front film. For comparison, the reference c-Si curves are presented. Throughout the wavelength range of 300-1200 nm, reference c-Si exhibits strong reflection. The reflection at 600 nm wavelength is significantly high at almost 40 % due to an abrupt change in refractive index (n) when the incident light travels from the air (n=1) into a medium which in this case is c-Si (n=3.5). Furthermore, for wavelength above 900 nm, transmission is high, reaching 50 % at 1100 nm. This is due to the thin c-Si inability to absorb long-wavelength light in a single pass [13]. The citation broadband absorption of c-Si is low, with just 60 % absorption at 600 nm.

Therefore, with thin c-Si solar cells, an ARC is required to improve absorption. With the help of multi-layered ARC, the light will go through a different medium from the air hence going through multiple incident angles. The reflection of light at 600 nm is low which is within 15-25 %. Some of the dispersed light is caught in the c-Si absorber after going through total internal reflection. Therefore, multilayer of anti-reflective coating was used mainly in photovoltaic applications compare to single or double layer due to higher broadband anti-reflective coating [13]. Saravanan *et al.* also reported that using multilayer, when number of stacks was increased, the reflectance was also enhanced [14]. Zambrano *et al*. observed that a 4-layer system with alternating TiO_2 and SiO_2 deposited on glass and obtained a reflectance of less than 2 % in visible range 400 to 750 nm [10]. Reflection losses on front surface of solar cells, affecting the performance of solar cell and enhance the effectiveness of the solar cell.

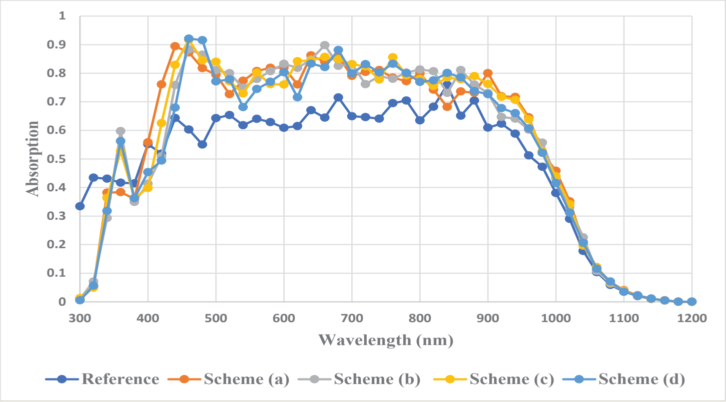
Figure 3 (b) shows the transmission of the long-wavelength in multi-layered ARC does not see major changes due to the increased light scattering. The broadband light absorption increases significantly between 75-85 % at 600 nm wavelength with present of multi-layered TiO_2/SiO_2 anti-reflective coating in Figure 3(c). The absorption of incident photon was enhanced and thus increase photo-generated current, which does have powerful impact on the efficiency of solar cell.



(a)



(b)



(c)

Figure 3 (a) Reflection, (b) Transmission, and (c) Absorption curve for thin c-Si (100 µm thickness) with different thicknesses of SiO_2 and TiO_2 as ARC

Table 1 summarizes the calculated J_{max} of the thin c-Si with 100 µm thickness with SiO_2 and TiO_2 multi-layered ARC. Jmax enhancement is derived by comparing each scheme J_{max} to the J_{max} of the reference c-Si scheme. The reference c-Si without ARC layer has J_{max} of 24.93 mA/cm^2. By implementing multi-layered ARC into thin c-Si, we can obtain enhance the efficiency from 19.57 to 21.46 % in comparison to thin c-Si. The rate of efficiency is increased because by using distinct layers to absorb different wavelengths of incoming sunlight, multi-layered solar cells are more efficient at converting sunlight into electricity. A multi-layered solar cell has more than one p-n junction. In fact, this means that there are numerous layers of different semiconductor materials, each of which responses to distinct wavelengths of light by producing electric currents. This means that multi-junction solar cells should theoretically be able to convert more sunlight into power.

Table 1: Data of the LT scheme with the total of Jmax and Jmax enhancements in percentage.

LT Sheme	J_{max}(mA/cm^2)	J_{max} enhancement (%)
Reference c-Si (thickness=100µm)	24.93	
Scheme (a): TiO_2 ARC with the thickness of 18 nm and 115 nm while SiO_2 ARC thickness of 26 nm and 102 nm	29.94	20.10
Scheme (b): TiO_2 ARC with the thickness of 19 nm and 124 nm while SiO_2 ARC thickness of 29 nm and 106 nm.	29.81	19.57
Scheme (c): TiO_2 ARC with the thickness of 19 nm and 120 nm while SiO_2 ARC thickness of 27 nm and 108 nm.	30.23	21.26
Scheme (d): TiO_2 ARC with the thickness of 19 nm and 123 nm while SiO_2 ARC thickness of 29 nm and 110 nm.	30.28	21.46

CONCLUSION

In this work, ray tracing of multi-layered anti-reflective coating in thin c-Si with 100 µm thickness were studied using four different thickness combinations of multi-layered SiO_2 and TiO_2. The effect of ARC on reflection, absorption, transmission, and Jmax enhancement of the incident light in the thin c-Si were investigated. From the obtained data, J_{max} was calculated within the wavelength of 300-1200 nm region to relatively estimate the efficiency of each scheme combination of thickness. From this work, it is proven that a multi-layered solar cell is significantly more effective than a single-layer solar cell. The reflection can be reduced much lower while the absorption has been boosted higher with the help of the multi-layered ARC. With Scheme (d) TiO_2 ARC with the thickness of 19 nm and 123 nm while SiO_2 ARC thickness of 29 nm and 110 nm, the J_{max} value is highest at 30.28 mA/cm^2 which contributed to 21.46 % of J_{max} enhancement which is the highest value in this work. To improve the efficiency of the ARC, the optical losses in the c-Si which are contributed by reflection in the short and long wavelength region need to be minimized.

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