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Numerical analysis of MgF_2/SiO_2 bilayers anti-reflective coating of light trapping in silicon solar cells by ray tracer software

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Anti-reflective coating (ARC) application is continuously being developed extensively and widely for the manufacture of coatings on the surfaces of optical devices which are hugely essential, desirable, and required, particularly on silicon solar cells. Single layer ARC is sufficient, but double layer ARC tremendously enhances solar cell efficiency by covering a wider range of the solar spectrum. Magnesium fluoride, MgF_2 and silicon dioxide, SiO_2 are the ARC coatings used in this work, with wavelengths in the range from 300 to 1200 nm. The optical properties of bilayer ARC coatings were obtained by varying the thickness of the double coatings and see how the ARC effects Si solar cells. Wafer ray tracer was used in PV Lighthouse software to simulate and model MgF_2 and SiO_2 bilayer ARC coatings in order to fully understand the performance and impacts of the coatings on Si solar cells. This simulation work contains the analysis of reflection, absorption, transmission, and J_{max}, which have been compared to many other theoretical results gathered from other studies and researches. To conclude, the absorption of the wavelength is highest between 500 nm to 900 nm leads to lowest reflection. The output shows that bilayer anti-reflective coatings with the thickness of 75 nm MgF_2 and SiO_2 are much more effective where the value of J_{max} is reach 32.80 mA/cm$_2$. The J_{max} enhancement compare to reference is 27.13% is achieved.

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1. Introduction

Due to current technological advancements, the consumption of solar cells is developing nowadays. This growth has been aided by advancements in materials and manufacturing processes. However, there are other challenges and issues that must be addressed before the photovoltaics (PV) can provide clean, abundant, and affordable energy for people convenience. The issues are particularly with regard to reflection loss. Whenever sunlight shines on the front surface of solar cells, some of light energy is transmitted into the cell and converted to electrical energy, while the rest is reflected from the front surface. Various methods have been used to reduce the loss caused by reflection on the silicon surface. The most commonly used approaches to minimize the loss due to reflection include light trapping, surface texturing, and anti-reflective coatings (ARC) [1].

ARC is a technique for reducing reflection and increasing light absorption in solar cells, hence enhancing their efficiency [2]. It is indeed best known for being the fundamental thin films used in optics. The anti-reflective coating has a numerous advantage, including maximum light transmission and thus increased the overall efficiency of the solar cells. The glare from the glass will also be minimized, which is a plus. Since the reflection of bare silicon solar cells is about 30%, this anti-reflective coating is both necessary and crucial [2]. It seems to be an important component of PV systems and has a broad range of applications. Texturing and applying an anti-

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reflection coating to the surface will lead to low reflection. Solar cells contain anti-reflection coatings similar to those found on camera lenses as well as other optical equipment.

One of most significant properties of optimum ARC and their appropriate representations can be specified in terms of reflectance and transmittance against wavelength, regardless of whether the cells originally produced with a single layer or many layers of ARC [3]. Light reflection from a single coating layer's outer surface interferes with light reflection from the coating layer's interface with the base, which would be the primary underlying principle of ARC. ARC is made up of very thin layers of various dielectric materials that are vacuum-coated onto both surfaces of the lens. The quality of the ARC coatings is determined by the amounts of layers applied to the lens.

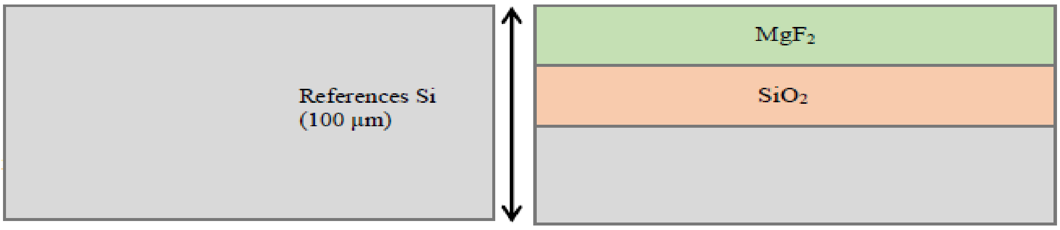
In order to increase the overall working efficiency, different types of ARC were extensively utilized in optics to eliminate undesired reflections in light-emitting diodes, display panels, solar cells, and sensors [4]. Several modelling and experiments on the development of single, bilayer, and multilayer ARC have been conducted in recent years. Single-layer anti-reflection coatings, from the other hand, have a limited bandwidth and lack Omni directionality due to a lack of inorganic material with a low index of refraction. Bilayer, multilayer, or graded-index ARC satisfies requirements which make them more efficient throughout a wider range. The most extensively used bilayer ARC that relies on a limited number of desired composite materials, such as TiO_2-SnO_2, TiO_2-SiO_2, and ZnO_2-SiO_2 [4].

So, for further propose, in this study, MgF_2/SiO_2 is applied for bilayer ARC of light trapping in a silicon solar cell by using wafer ray tracer. To further research, different ARC of various thicknesses is coated to silicon solar cells.

2. Experimental work

Wafer ray tracer is used for photovoltaic simulator in this study. This software is frequently used based on several advantages that it produces such as this software gives more thorough and precise results, which assist to measuring the photo generated current density in a solar cell or simulating the structure under a chosen illumination wavelength, based on the data that we input into the tracer. It could be used to analyse or improve the optical characteristics of a solar cell. Not only that, but this software has also generated curves for reflection, absorption, and transmission based upon the data entered to make plotting graphs much easier. Additionally, PV Lighthouse software is much uncomplicated and immeasurably easier to use and gain data compare to other software.

For this research, the bilayers anti reflective coatings used were magnesium fluoride, MgF_2 and silicon dioxide, SiO_2. The thickness for SiO_2 are fixed which is at 75 nm while the thickness for MgF_2 are varied which are 75 nm, 100 nm, 115 nm and 122 nm as shown in Figure 1. The structure of the surface is fixed to planar structure. The spectrum used was sunlight with AM 1.5g which refers to Air Mass 1.5 spectra that was designed for flat lines panels with integrated power of 1000 W/m_2 or 100 mW/cm^2 at zero angle of incident [5]. For the ray tracing, the maximum total rays used is 50 000 and the number of rays per run is 5000 with 1000 maximum bounces per ray with 0.01% intensity limit. The optical properties of the silicon solar cells are studied based on the range of wavelength with minimum wavelength of 300 nm up to maximum wavelength which is 1200 nm with wavelength interval of 20 nm.



(a) (b)

Fig. 1. (a) Reference: Schematic diagrams of Light Trapping schemes in silicon solar cells without anti reflective coatings (as a reference) for planar solar cells; (b) MgF2 ARC for Si solar cell with thickness of 75 nm.

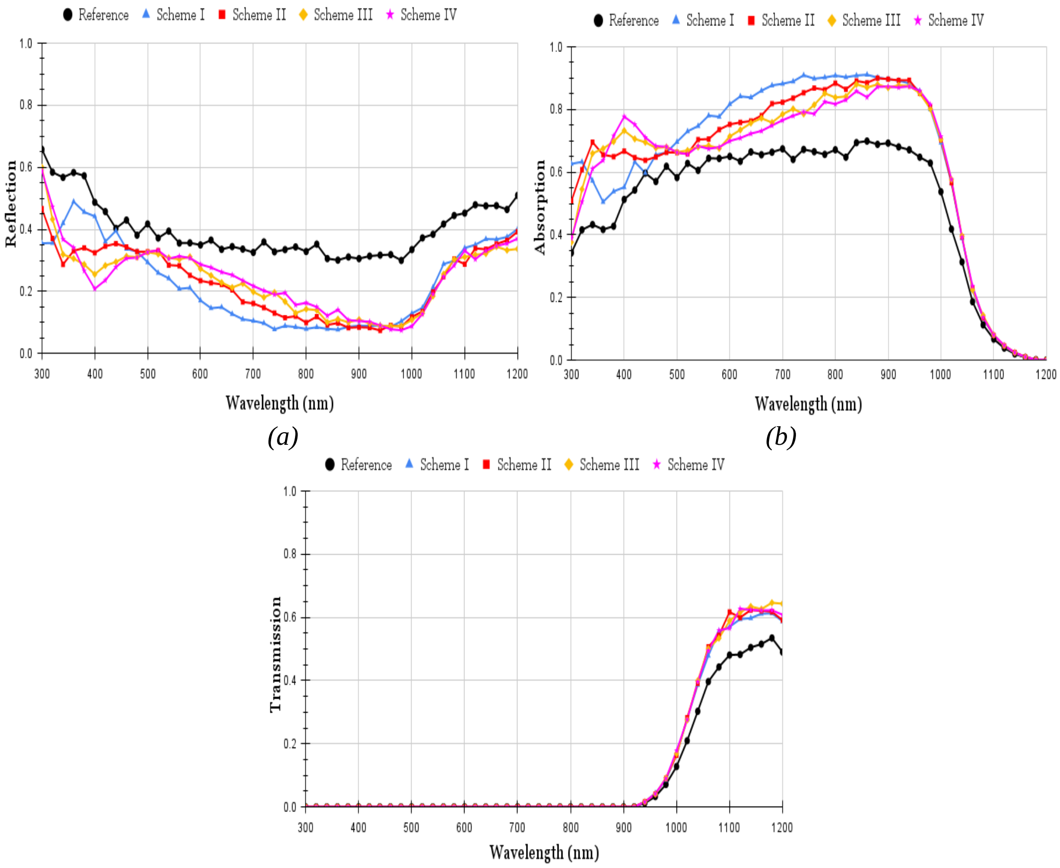
In the simulation, the results for reflection, absorption and transmission and was tabulated. The short-circuit current and the light-generated current are comparable for a perfect solar cell with just minimal resistive loss mechanisms. As a result, the maximum current that can be generated from a solar cell is the short-circuit current. The optimum current density of silicon solar cells, J_{SC} and short current density, I_{SC} was looked over and analysed further based on the schematic schemes above. Light trapping efficiency of Si solar cells is evaluated by using formula of the wavelengths of 300–1200 nm over the AM1.5 solar spectrum [6]. Below is the formula of J_{max}:

$$J_{max} = q \int_{\lambda=300\ nm}^{\lambda=1200\ nm} EQE(\lambda).S(\lambda)d\lambda \tag{1}$$

In addition to the optical properties, the current density will be studied extensively by using J_{max} formula.

3. Result and Discussion

The curves for reflection, absorption, and transmission for a 100 µm silicon solar cell are included in the Figure 2 below. A reference graph is included once to analyse and compare the differences between the four different LT schemes.



(a) *(b)*

(c)

Fig. 2. a) Reflection b) Absorption c) Transmission curves for silicon solar cells with different thickness of 75 nm, 100 nm, 115 nm, and 122 nm. Reference curve of silicon solar cells (black curve) included for comparison.

Figure 2 a) exemplifies that the reflection for the reference curve is at its peak, without anti-reflective coating. When MgF_2 coating were added up to 75 nm thickness (Scheme I), it shows that the curve is at the highest points at wavelength ranging from 300 nm to 400 nm, but it dramatically decreases from wavelength of 400 nm and above. This change is contrasting very much compared to when the thickness of MgF_2 increases up to 122 nm (Scheme IV). This revelation demonstrates that by increasing the thickness of the coatings lessens silicon solar cell reflectance. Considering that the ARC coating does indeed have a quarter wavelength coating effect, which would be intended to minimize wide reflection and increase light absorption into silicon solar cells, which is to be predicted [7]. Thus it clarifies to explain why the curves in the reflection graph have different patterns where the reference curve is the highest because it has the highest reflection compare to other schemes. The effective reflectance of a typical bilayer AR coating decreases significantly and approaches zero at the particular wavelength before gradually increasing, resulting in a virtually V-shaped reflectance curve in the observed spectral range [8]. Therefore, due to the fact that the optimized bilayer anti reflective coatings of MgF_2 and SiO_2 have such a significantly reduced average reflection because both coatings have two minimum reflection points as well as a spectrum of wavelengths where the reflection is lowest [9]. Reflection losses occur on the top surface of solar cells, affecting the solar energy production performance. On that account, by adding anti-reflective coatings, it helps to minimize the reflection loss and enhance the effectiveness of the solar cell.

The absorption graph in Figure 2 b) raises in a brief range of wavelength for the reference curve, but then declines as the wavelength increases. Contrasting to the fact when MgF_2 coating were applied to 75 nm thickness (Scheme I) to the Si solar cell, the absorption curve increases the highest compared to other schemes between wavelength of 500 nm to 900 nm but gradually declines later. Contrasting to the curve of 122 nm (Scheme IV) where it at the highest point at 400nm but later, it declines lower than the curve of Scheme I. This signifies that the absorption of incident photons was somehow enhanced, and thus the photo-generated current, which does have a profound impact on the efficiency of solar cell [10]. Light absorption in silicon solar cells rises across the whole wavelength range based on the sheer enhanced light absorption caused by ARC. It denotes an increase in incident photon absorption that has a substantial impact on solar cell efficiency [11]. Hence, this explains the difference between the absorption curves for different thickness of MgF_2 coating.

Lastly, in Figure 2 c) explains the transmission curve for Si solar cell. The curves for all thickness (Scheme I - Scheme IV) are the same for wavelength ranging from 300 nm to 900 nm. However, there is a slight change as the wavelength increase from 900 nm and above where the curve for reference is the lowest among all schemes. Yet, between wavelength of 1100 nm and 1200 nm, curve for Scheme I is the lowest. This implies that MgF_2 coatings with a thickness of 75 nm seemed to have the weakest transmission of solar cell. Lower absorption and higher current and voltage density are further features of ARC coatings, contributing to improved productivity of solar cell [10]. Thus, it defines on why there is difference between those transmission curves between the schemes.

Table 1. Summary of the J_{max} values for Si solar cell with 100 μm based on the LT schemes, between the ranges 300-1200 nm wavelengths. Reference Si solar cell without ARC is included for the comparison between the LT schemes.

LT scheme	**J_{max} (mA/cm^2)**	**J_{max} enhancement (%)**
Reference Si solar cell without ARC with 100 μm	25.80	-
Scheme 1: MgF_2 ARC for Si solar cell (thickness = 75 nm)	32.80	27.13
Scheme II: MgF_2 ARC for Si solar cell (thickness = 100 nm)	31.82	23.33
Scheme III: MgF_2 ARC for Si solar cell (thickness = 115 nm)	31.22	21.00
Scheme IV: MgF_2 ARC for Si solar cell (thickness = 122 nm)	30.87	19.65

Table 3 above explains that when the thickness of MgF_2 increases, the value of J_{max} as well as value of J_{max} enhancement wills decreases. This revelation clarifies that by adding MgF_2 as anti-reflective coatings helps to boost the enhancement of Si solar cell. Double layer coatings particularly ideal for optical applications that demand very little reflection at the wavelength generated [8].

Getting an accurate measurement of EQE is amongst the most beneficial methods to improve the efficiency and effectiveness of solar cell consumption. As stated previously, EQE stands for 'External Quantum Efficiency,' where QE indicating to the ratio of the total number of carriers absorbed by the solar cell to the number of photons incident on the solar cell of a certain energy. Due to the obvious photo enhancement effect and the necessity for monochromatic detecting radiation, QE is intimately linked to photo-generated current, as well as its measurement is very much important. Since monochromatic light has been used in QE measurements, majority studies were likely to observe and distinguish solar cell characteristics in a particular spectrum of various wavelengths. The term EQE refers to the effect of optical losses such as transmission and reflection on a silicon solar cell. Nonetheless, once the reflected and transmitted light has indeed been absorbed, it is sometimes helpful to look at the quantum efficiency of the light which remains.

4. Conclusion

As a summary, this simulation shows that bilayer anti-reflective coatings with 75 nm thickness of MgF_2 are much more effective among other LT scheme. J_{max} value increased to 32.80 mA/cm^2 compared to the references scheme leads to enhancement of 27.13%. Highest absorption for Scheme 1 is occurring within wavelength 500 nm to 900 nm. This signifies that the absorption of incident photons was somehow enhanced, and thus the photo-generated current, which does have a profound impact on the efficiency of solar cell. Although, the effectiveness of MgF_2 as ARC is not truly remarkable, it is indeed a significant improvement over an uncoated surface since MgF_2 has a broad transmission range that can helps the increased of absorption in the Si solar cells.

Acknowledgments

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