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Comparing of The Performance of Single and Double Layer Anti-Reflection (ARC) Coatings on Solar Cell Efficiency By PC1D

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Abstract

With the expansion of the spread of solar energy in recent years, its applications are in many fields, and the trend of consumers towards it as energy-saving and environmentally friendly, working to raise its efficiency is something that has become important to pay attention to, and anti-reflection coating (ARC) is one of the most important factors that increase the efficiency of the solar cell from by reducing reflection losses, raising the absorption factor, and enhancing the conversion efficiency (PCE), the efficiency of solar cells varies depending on the type of ARC material used and its properties. Therefore, in this study, simulations of 6 different anti-reflective coating materials (ARC) were analyzed in terms of their performance to increase the cell efficiency. Using the PC1D simulation software, the results revealed that at the wavelength of 550 nm, the MgF_2/CdS *coating would be the best ARC for the two-layer ARC design due to its highest efficiency of 27.85%.*

Keywords: **Solar cell, Anti-reflection coating, PC1D, Photovoltaic, Optical properties, Electrical properties**

1. Introduction

With increasing severity of the impact of climate change on the world and the phenomenon of global warming, the search for safe energy sources has become a necessary solution that occupies every researcher interested in protecting the planet Earth and achieving sustainability. Photovoltaic energy is one of the most important energies that plays an important role in achieving sustainability, as it enjoys many advantages, including wide spread and friendliness. Therefore, it can be considered one of the most feasible solutions to achieve environmental sustainability.

One of the problems of solar cells is that they need to process partially reflected sunlight, making Chris efficiently, as the refractive an isotropy between materials increases, the an isotropy can be reflected by Fresnel equations, for example in the case of surface and color silicon, 35% of the light can be reflected[1][2]. Various methods are used to solve this common problem of reflections by coating the surface with an anti-reflection layer. An anti-reflection coating consists of one or more thin layers of a transparent material with a refractive index equal to the square root of the refractive index of the substrate and the refractive index of the surrounding medium. By reducing the contrast of refractive index between media the reflection is reduced, which can be calculated by the Fresnel equation. Anti-reflection coatings can be achieved by using a variety of materials such as porous silica nano particles on a polymer substrate, zirconium and its oxides, and magnesium fluoride. This research will compare between single-layer and double layer anti-reflection coating (DLARC) of the following materials: MgF_2, Al_2O_3, ZnS, ZnO, CdS and SnO_2.

The comparison was made in terms of lower reflectivity and higher solar cell efficiency through virtual simulation using the website www.pveducation.org.

The reflectivity of a single layer is calculated by the following equation:

$$R = |r^2| = \frac{r_1^2 + r_2^2 + 2r_1r_2\cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1r_2\cos 2\theta} \qquad (1)$$

Where:

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$$

$$r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

$$\theta = \frac{2\pi n_1 t_1}{\lambda}$$

We define a series of parameters r_1, r_2, and θ. The surrounding area has a refractive index of n_0. ARC has a refractive index of n_1. Thickness t_1 of silicon has a refractive index of n_2. As for the reflectivity of two layers, it is calculated by the following equation:

$$R = |r^2| = \frac{A}{B} \qquad (2)$$

Where:

$$A = r_1^2 + r_2^2 + r_3^2 + r_1^2 r_2^2 r_3^2 + 2r_1 r_2 (1 + r_3^2)\cos 2\theta_1 +$$

$$2r_2 r_3 (1 + r_1^2)\cos 2\theta_2 + 2r_1 r_3 \cos 2(\theta_1 + \theta_2) + 2r_1 r_2^2 r_3 \cos 2(\theta_1 - \theta_2)$$

$$B = 1 + r_1^2 r_2^2 + r_1^2 r_3^2 + r_2^2 r_3^2 + 2r_1 r_2 (1 + r_3^2)\cos 2\theta_1 +$$

$$2r_2 r_3 (1 + r_1^2)\cos 2\theta + 2r_1 r_3 \cos 2(\theta_1 + \theta_2) + 2r_1 r_2^2 r_3 \cos 2(\theta_1 - \theta_2)$$

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$$

$$r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

$$r_3 = \frac{n_2 - n_3}{n_2 + n_3}$$

$$\theta_1 = \frac{2\pi n_1 t_1}{\lambda}$$

$$\theta_2 = \frac{2\pi n_2 t_2}{\lambda}$$

The equations for multi-layer anti-reflection are more complex than those for single-layer, first we define a series of parameters r1, r2, r3, θ1 and θ2 the surrounding area has refractive index n0, the next layer has refractive index n1 and thickness t1 , and the layer directly above the silicon has a refractive index n2 and its thickness is from t2 and the silicon has a refractive index n3.

The coatings used in solar cells are similar to those applied in various optical equipment such as camera lenses, and these coatings consist of an insulating material, with a certain thickness that depends on equation (3), so that this thickness leads to interference effects in the coating to the reflected wave emerging from the upper surface of the anti-reflection coating. Out of phase with the reflection of the wave from the surfaces of the semiconductor (solar cell), these two waves destructively interfere, leading to zero net reflected energy.

$$d = \frac{\lambda_{\circ}}{4\, n_s} \qquad (3)$$

The thickness, which determines the minimum reflection of the anti-reflection layer, is determined so that the wavelength in the insulating material is one-quarter of the wavelength of the incident wave.

$$n_s = \sqrt{n_\circ \, n_2} \qquad (4)$$

Through equation (4), the refractive index of the anti-reflection layer is determined, at which the lowest level of reflection occurs, and the refractive index is the geometric mean of the materials on both sides of the anti-reflection layer, i.e. glass, air, and semiconductor (solar cell). Solar panels consist of a number of components known as solar cells that are manufactured separately and depending on the power required solar panels are built in both parallel and series [1]. In a solar cell, the P-N junction divides the electron carriers and holes to generate a voltage and work to move the charges. It requires a photon with an energy greater than the band gap of the semiconductor material that is built from the PN junction of a solar cell in order to generate electricity. The electrons in the valence band pick up this photon and then flow from there to the conduction band where they can generate an electric current, and the energy of the photons must not decrease than 1.12 volts for silicon with an effective bandgap of 1.12 e.V [3]. The wavelength can be found through energy with the following equation:

$$\lambda(nm) = \frac{1.240}{E(eV)} \qquad (5)$$

Where E is the energy in electron volts, for silicon the wavelength is set to be about 1,107 nm and waves of that wavelength or less generate an electron-hole pair [3].

The performance of a solar cell can be evaluated using the conversion efficiency of solar cells, where efficiency is expressed as a ratio between the energy entering the cell and the energy leaving it, as shown in Equation 6:

$$\eta_{max} = \frac{p_{max}}{E * A_c} \times 100\% \qquad (6)$$

where : η represents the solar cell efficiency, Pmax indicates the maximum output power (W), E is the incident radiation flux (W m^{-2}) and Ac is the area of the collected current (m^2). The input power can be calculated from the following equation:

$$p_{in} = I_{light} \times A \qquad (7)$$

where: I_{light} is the incident light intensity, which is equivalent to ٠٫١ w cm^{-2} for radiation of 1.5AM, and A is the surface area of the solar cell, and the fill factor (FF) of the silicon solar cell is calculated using the following formula:

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} \qquad (8)$$

where: FF represents the fill factor of the solar cell, P_{max} is the maximum power output (W), V_{oc} is the open circuit voltage and I_{sc} is the short circuit current.

2. PC1D

An application to simulate the anti-reflective coating system and the solar cell is available from the pveducation website, which is a website specialized in photovoltaic energy and is considered an e-book that explains the concept and characteristics of photovoltaic energy and its related applications, including anti-reflective coatings. The site provides many parameters of crystalline semiconductors that can be used in energy technology. Solar materials such as gallium arsenide (GaAS), silicon (Si), indium phosphate (InP), germanium (Ga), AlGaAS, and InGaAs.

The site is also easy to use and provides many outputs to researchers such as current density, primary current, energy, diffusion length, doping density, quantum efficiency, and much more.

In this study, as shown in Table (1), the basic parameters were chosen. The area of the device was set to 110 square centimeters, the external front reflection was set to 10%, the thickness of the first area was constant, as was the second, and both areas were made of silicone. The doping was adjusted.

The background is of the type P and N. In the excitation region, the selected parameters were from the transient excitation mode. Both the intensity and the solar spectrum were adjusted. ARC materials were applied in the external front reflection located under the device.

Table 1: Solar Cell Parameters Used in the Simulation.

Parameter	**Value**	**Reference**
Device		
Device area	110 cm2	
Surface texturing	None	[4]
Surface charge	None	
Exterior front reflectance	10%	
Exterior rear reflectance	None	
Internal optical reflectance	None	
Region 1		
Thickness	10µm	[4]
Material	Silicon	
Dielectric constant	11.9	
Band gap	1.124eV	
Intrinsic concentration	1×1010cm-3	
Refractive index	Fixed	
Absorption coefficient	Enabled	[5]
Free carrier absorption	Enabled	
N-type background doping	10×1018cm-3	
Bulk recommendation	1000µs	[6]
Region 2		
Thickness	100µm	[4]
Material	Silicon	
Dielectric concentration	11.9	
	1.124eV	
	1×1010cm-3	
Refractive index	Fixed	[5]
Absorption coefficient	Enabled	
Free carrier absorption	Enabled	
P-type background doping	10×1017cm-3	[6]
Bulk recommendation	1000µs	
Excitation		
Excitation mode	Transient,16 timesteps	
Temperature	25ºC	
Base circuit	-0.8 to 0.8 V	
Collector circuit	0	
Primary light source	Enabled	
Constant intensity	0.1 Wcm-2	
Spectrum	Am 1.5 g	
Secondary light source	Disabled	

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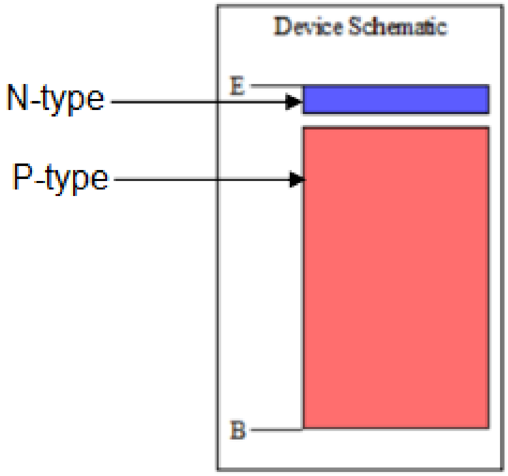

Figure 1: Schematic of the solar cell device as set up in PC1D. The diagram shows the P-type (red) and N-type (blue) regions, with the emitter (E) and base (B) clearly labeled

Figure 1 above shows the structure set as the main structure for the solar cell simulation using PC1D and the solar cell schematic device. The red region is the P-type region and E represents the emitter while the blue region is the N-type region and the B region is the base [7]. The steps for simulating monolayer ARC in a silicon solar cell are illustrated as shown in Figure (2) below.

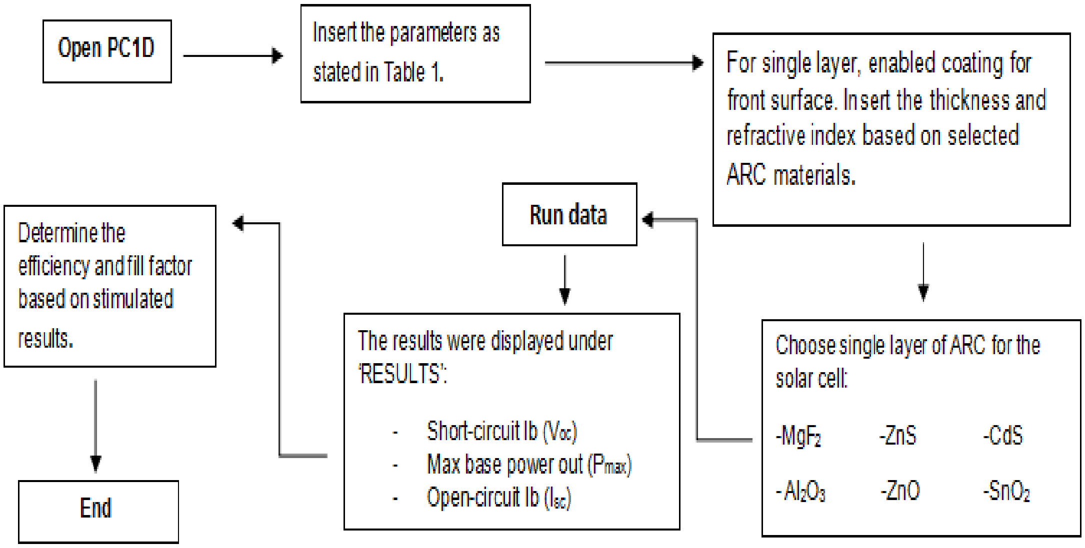

Figure 2: Diagram of simulating monolayer ARC in a silicon solar cell

The steps for simulating double layer ARC in a silicon solar cell are illustrated as shown in Figure (3) below.

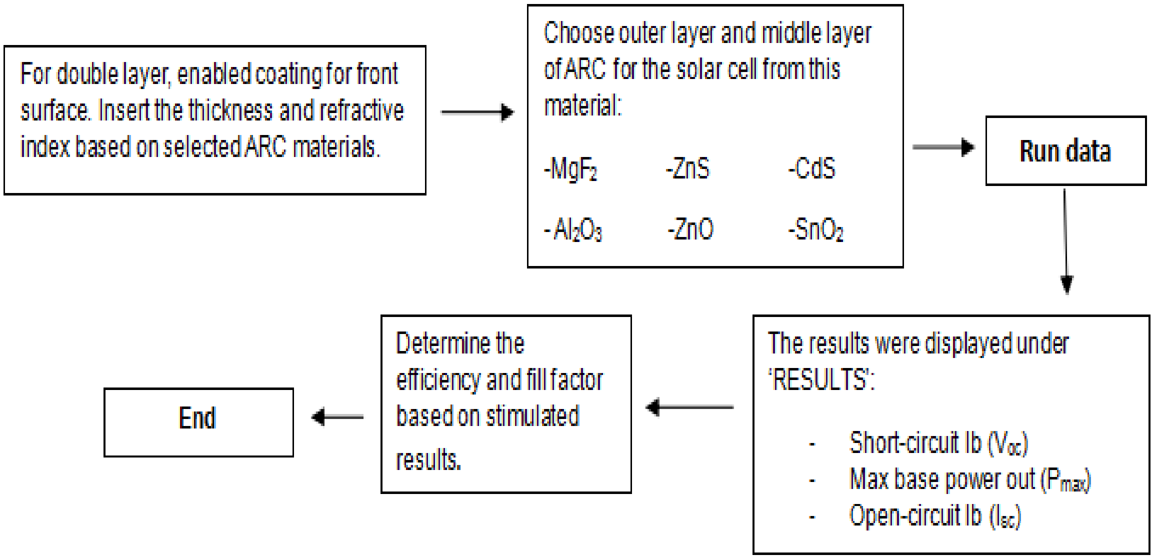

Figure 3: Diagram of simulating double layer ARC in a silicon solar cell

3. Results and discussion

The PC1D program was used to stimulate a silicon solar cell without anti-reflection coating, and the following results were produced as in Table (2)

Table 2: simulation results of a chosen silicon solar cell parameters without anti-reflection coating

P_{in}	P_{max}	V_{oc} V	I_{sc} A	FF	η%
0.1x110	2.380	0.7377	3.781	0.8532	25.35

Table 2 showed the PC1D simulation results when solar energy applied without any anti-reflection coating, where: Pin = 0.1 Wcm^{-2} ×110 cm^{-2}

The results for Voc: 0.7377 V were Pmax: 2.380 W and Isc: 3.781 A respectively. Hence, based on that data, the simulation efficiency without ARC was only 25.35% with a fill factor of 0.853203.

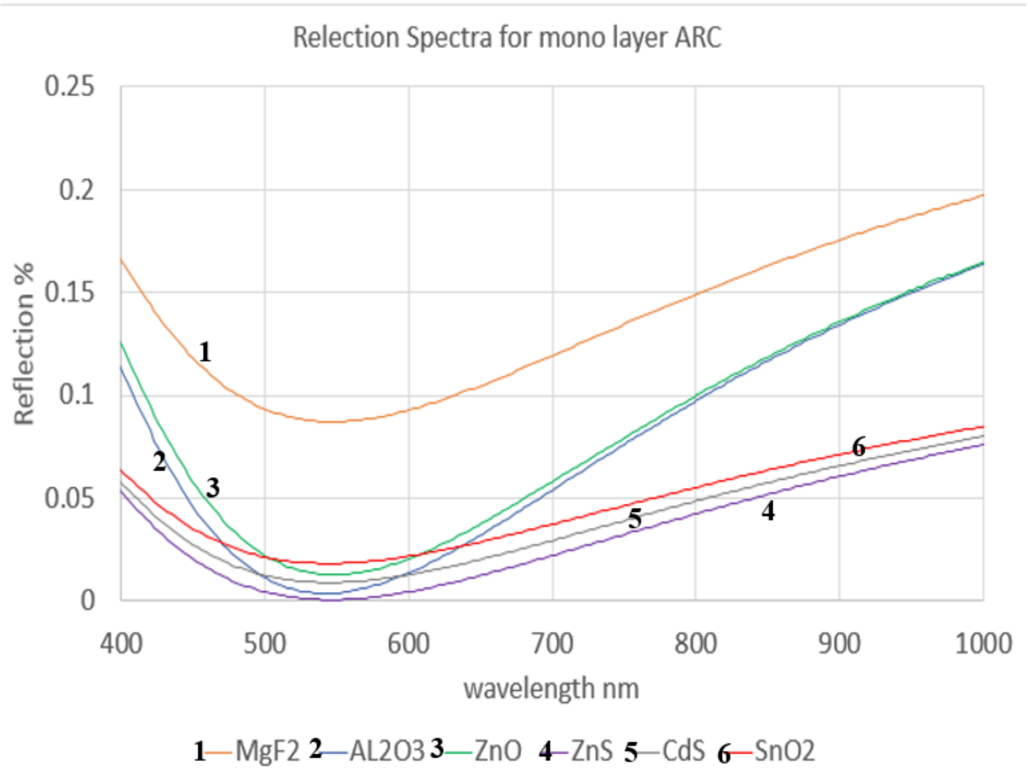

Figure 4: Reflectivity curves for various materials under air conditions across different wavelengths using www.pveducation.org.

Note: All materials exhibit minimum reflectivity at 550 nm, with ZnS achieving the lowest reflectivity (0.005) and CdS the highest (0.09).

It is clear from Figure (4) that all materials achieved the lowest reflectivity at wavelength 550, and that ZnS achieved the lowest reflectivity of 0.005, while Al_2O_3 achieved a reflectivity of 0.008, followed by MgF2, which achieved a reflectivity of 0.01, then ZnO. 0.017 and SnO2 0.02 and finally in last place comes CdS with a reflectivity of 0.09, so zinc sulphide will achieve the lowest reflectivity when applied in air while cadmium sulphide achieves the highest reflectivity.After applying the coatings to the solar cell, the results appeared as follows: Data for the various anti-reflection coatings used in PC1D are shown in Table (3) below.

Table 3: Data of the single-layer coatings used

The ARC	Thickness (nm)	Refractive index	Pmax(W)	Isc(A)	Voc(v)	FF	η
SnO_2	68.5	2.00	2.444	3.840	0.7384	0.8508	26.11%
Al_2O_3	77.7	1.76	2.437	3.879	0.7384	0.8508	26.03%
ZnO	82.3	1.67	2.419	3.848	0.7382	0.8515	25.82%
ZnS	58.6	2.35	2.771	3.766	0.7376	0.8535	25.25%
CdS	54. 3	2.52	2.308	3.665	0.7369	0.8545	24.55%
MgF_2	99.6	1.38	2.264	3.600	0.7365	0.8538	24.10%

Based on the results of Table (3), it was shown that different types of ARCS have different effects on the efficiency of the solar cell. It can be noted that SnO_2 has the highest efficiency, which is 26.11%, for a wavelength of 550 nm and a thickness of a quarter wavelength, while ranked Al_2O_3 second in efficiency 26.03 %, followed by ZnO with an efficiency of 25.82%, then ZnS with an efficiency of 25.25%,then CdS with an efficiency of 24.55% and the last one comes in the lowest ranking for the efficiency of ARC in simulating the solar system MgF_2 with an efficiency of 24.10%, and this is due to the low light reflection, which is the factor that This makes this efficiency achievable [6]. These results were fairly accurate and can be supported by previous studies. The 550 wavelength corresponds to the visible region of the sun's AM 1.5 g radiation. According to the UCAR COMET program, approximately 43% of the sun's radiated energy lies in the visible region.[8][9]

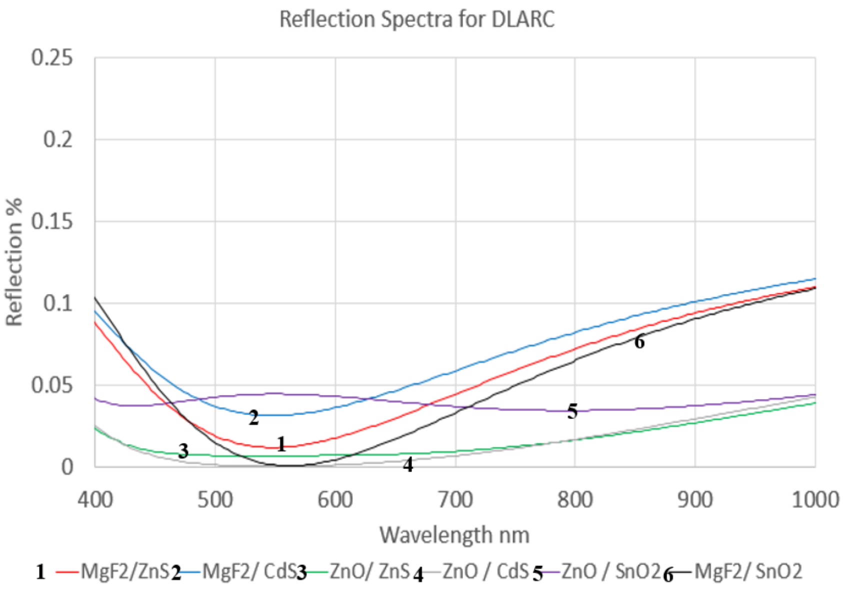

Figure 5: Reflectivity curves for double-layer ARCs under air conditions across different wavelengths using www.pveducation.org.

Note: The double-layer ARCs generally achieve lower reflectivity values (ranging from 0.006 to 0.04) compared to single-layer ARCs.

It is clear from Figure (5) that all the bilayers achieved the lowest reflectivity at the wavelength of 550 nm. The ZnO/CdS layers and the MgF_2/SnO_2 layers were the least reflective, with a reflectivity close to zero, estimated at 0.006. These two layers were ZnO/ZnS with a reflectivity of 0.01, then MgF_2/ CdS with a reflectivity of 0.018, then MgF_2/CdS with a reflectivity of 0.03, and in last place came ZnO/SnO_2 with a reflectivity of 0.04, and compared in terms of reflectivity between it and while the monolayer reflectivity range was between 0.005 and 0.09, the reflectivity of the double layer was lower, as its reflectivity range ranged between 0.006 and 0.04.

When these two-layer coatings were applied to the solar cell in the simulation, these data were found:

Table 4: Data of the two-layer coatings used

The ARC	Pmax(W)	Isc(A)	Voc(v)	FF	η
MgF_2 / CdS	2.619	4.140	0.7400	0.8548	27.85%
ZnO / CdS	2.611	4.129	0.7399	0.8546	27.77%
MgF_2 / SnO_2	2.589	4.099	0.7397	0.8538	27.56%
ZnO / ZnS	2.539	4.044	0.7394	0.8480	27.21%
MgF_2 / ZnS	2.534	4.042	0.7394	0.8478	27.16%
ZnO / SnO_2	2.404	3.822	0.7380	0.8522	25.64%

Based on the results of Table (4), it was shown that the different types of two-layer ARC have different effects on the efficiency of the solar cell. It can be noted that MgF2/CdS has the highest efficiency, 27.85%, at a wavelength of 550 nm and a thickness of a quarter wavelength for both layers, while the ZnO/CdS ranked second with an efficiency of 27.77%. The MgF2/SnO2 coating achieved third place with an efficiency of 27.56%. Then comes

ZnO/ZnS with an efficiency of 27.21% and MgF2/ZnS with an efficiency of 27.16% . Finally, the ZnO/SnO2 coating achieved the lowest efficiency of 25.64% in simulating the solar system. It is noted that the performance of the second layer coatings is better. Significantly, the efficiency of all double-layer coatings increased over the single-layer coatings, except for the ZnO / SnO2 coating, which achieved an efficiency close to the performance of the single-layer coating.

The single-layer coating with SnO_2 achieves the highest efficiency (26.11%). This superior performance is attributed to its optimal refractive index and quarter-wavelength thickness at 550 nm, which effectively minimizes reflectivity and enhances light absorption.

Among the double-layer ARCs, the MgF_2/CdS combination exhibits the highest efficiency (27.85%). The improved performance of double-layer coatings is primarily due to the enhanced interference effects that further reduce reflectivity beyond what is achievable with single-layer coatings. The synergy between MgF_2 in the upper layer and CdS in the lower layer creates an optimal optical environment, leading to improved solar cell performance.

So, if we want to point to the effect of material and layer thickness it is noted that the performance of the material in the ARC layer is directly related to the refractive index and layer thickness; SnO_2achieves outstanding performance in the monolayer refers to its coefficient matching ideal conditions for destructive interference.

But for bilayers provide a significant improvement in efficiency, as the combination of MgF_2 in the top layer and CdS in the bottom layer reduces reflection to levels below those available in monocoating, contributing to increased solar absorption and improved overall cell performance.

4. Conclusion

In this study, the design and modeling of silicon solar cells were manufactured and coated with different materials of one layer and two layers of anti-reflection coatings (ARC) using the PC1D program. The optical properties of the solar cell were studied within the 550 nm wavelength region in the optimal reflection state, and based on the simulation, conclusions were made. Two-layer coatings are the best in increasing the efficiency of the silicon solar cell compared to single-layer coatings. The coating consisting ofMgF2 with a thickness of 99.6 nanometers and a refractive index of 1.38 as the upper layer and a lower layer of CdS with a thickness of 54.36 nanometers and a refractive index of 2.52 has the highest efficiency of 27.82% compared to two-layer coatings and coatings.

Also, single layer with a thickness of 153.96 nanometers, this coating generates an open circuit voltage of 2.825 volts and an open circuit current of 4.140 amperes with a maximum power of 2.619 watts as well as a fill factor value of 0.8548, which makes this type of coatings the best in increasing the efficiency of a silicon solar cell, as for the single-layer SnO_2 coating With a thickness of 68.54 nanometers and a refractive index of 2.006, it is the highest in efficiency, which is 26.11% compared to single-layer coatings. With a thickness of 68.54%, this coating generates an open circuit voltage of 0.7384 volts, a current of 3.840, a maximum power of 2.444 watts, and a fill factor value of 0.8508. When choosing a single layer, SnO_2 it is the candidate for achieving high efficiency. All the materials presented in this study help provide recommendations as well as data regarding the materials that have the greatest potential for application to silicon solar cells. In conclusion, the MgF_2/CdS coating is the best ARC material that can be applied to solar cells to enhance the efficiency of the silicon solar cell. In general, the Double-layer coatings achieve higher efficiency than single-layer coatings.

This study demonstrates that applying anti-reflection coatings significantly enhances the efficiency of silicon solar cells. In particular, the double-layer ARC composed of MgF_2(upper layer) and CdS (lower layer) achieves an efficiency of 27.85%—a notable improvement over the 25.35% efficiency of a cell without any ARC.

The improved performance with double-layer ARCs suggests that such configurations can be beneficial in designing high-efficiency solar panels, and the results offer valuable guidelines for material selection and thickness optimization to minimize reflective losses in solar cell design.

Experimental validation of the simulated results is recommended to confirm the performance of these ARC configurations under real-world conditions, and further exploration of novel ARC materials and combinations could provide additional enhancements in solar cell efficiency, especially under varying environmental conditio

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References

[1] Adam M.Law, Luke O.Jones and John M.Walls (2023) The performance and durability of Anti-reflection coatings for solar module cover glass – a review: Solar Energy 261 (2023) 85-95.

[2] W. Abdullah,“Fabrication of SiO2-TiO2 Double Layers Anti-Reflection Coating by Sol- Gel Method and Study of its Optical Properties”International Letters of Chemistry, Physics and Astronomy, vol. 56, pp. 175-183, 2015.

[3] M Uniyal. PN Junction Solar Cell, Available at: https://byjusexamprep.com/pn-junction-solar-cell-i, April 2024.

[4] C. Jiang, T. Li, X. Zhang, and L. Hou, “Simulation of silicon solar cell using PC1D,” Adv. Mater. Res., vol. 7032-6, pp. 383-390, 2012.

[5] M. Belarbi, A. Benyoucef, and B. Benyoucef, “Simulation of the solar cells with PC1D, application to cells based on silicon,” Adv. Energy Mater., pp. 1-10, 2014.

[6] G. Hashmi, M. J. Rashid, Z. H. Mahmood, M. Hoq, and M. H. Rahman, “Investigation of the impact of different ARC layers using PC1D simulation: application to crystalline silicon solar cells,” Theor. Appl. Phys., vol. 12, pp. 327-334, 2018.

[7] Y. Jamaludin, Y. Yusoff, and Malek, “Modelling of High Silicon Solar Cell Using Various Anti Reflective Coatings (ARC),” Trends Sci., vol. 21, no. 3, pp. 7337-7345, 2024.

[8] Asrmeta, “What is a solar cell?” [Online]. Available: https://www.asrmeta.com/solar-cells-their-constructionand-working/. [Accessed: Apr. 2024].

[9] “Photovoltaic Cells – Silicon,” [Online]. Available: https://www.greenmatch.co.uk/solar-energy/solar-panels/photovoltaic-cells/silicon. [Accessed: Apr. 2024].