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Numerical Modelling of High Efficiency Silicon Solar Cell Using Various Anti Reflective Coatings (ARC)

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Abstract

The growing prevalence of solar in recent years, which is applied in practically every daily item comprehensively and broadly to make it simpler on consumers due to the consumption of solar resulting in a lot of savings. Anti-reflective coating (ARC) is one of the most important factors contributing to the extensive application of solar. It was acknowledged that ARC had been applied on solar cells to minimize reflection loss, enhance absorption, and boost power conversion efficiency (PCE). The efficiency of solar cell varies depending on the type of ARC material used and its specific characteristics. Since each anti-reflective coating originates from its own formula, there are many different materials produced and manufactured to be applied on solar cells. Hence, in this paper, the simulation of 6 different materials of anti-reflective coating (ARC) coatings has been analyzed and investigated using PC1D simulation software. The outcomes revealed that the ideal wavelength for developing and constructing an ARC would be around 500 and 800 nm. Silicon nitrite (Si_3N_4) would be the best ARC for designing a single-layer ARC due to its highest efficiency of 21.69 % and exhibits the lowest reflectance, closely followed by zinc oxide (ZnO) which has the efficiency of 21.67 %. Then, zinc sulphate (ZnS) and Titanium Oxide (TiO_2) has the efficiency of 21.16 and 21.05 % respectively. While, the silicon dioxide (SiO_2) has an efficiency of 20.23 % and lastly, silicon carbide (SiC) has lowest efficiency of 17.07 %. Based on the PC1D simulation software carried out in this research, the data and outcomes regarding the voltage, current, maximum power output, solar efficiency, fill factor, reflectivity, and external quantum efficiency are also reported.

Keywords: Silicon heterojunction solar cell, Anti-reflective coating, Photovoltaic, Optical properties, Electrical properties, PC1D

Introduction

Solar energy has indeed been extensively applied across the country, where solar panels are installed in a wide range of places including households, workplaces, schools, and other establishments, to replace the consumption of electricity and reduce the amount of waste. Solar panels have undergone a variety of modifications recently to travel in a more advanced route and improve the performance, which runs parallel to the rapid technological advancements. So, many research investigations have been conducted to develop solar technology which is more cost-effective and economical for efficient usage.

Pure silicon, which has been used as an electrical component for decades, is the fundamental aspect of a solar cell. Nearly 90 % of the market for solar cells today is silicon-based. Since very high-quality silicon was required to be manufactured in the past, silicon solar panels used to be quite pricey. Besides, the process of purifying silicone before contaminating it with gallium and arsenic atoms used to be labor-intensive and expensive [1]. A material for photovoltaic devices which is most known as silicon has special advantages. It really is not only among the most prevalent elements in the crust of the earth, but it's also a semiconductor element whose bandgap is very close to being a nearly exact fit to the spectrum of the sun [2]. Optimizing the efficiency of a specific solar cell could possibly be achieved through applying a good design for the cell and striving to have a minimal amount of reflection on its surface using an anti-reflective coating (ARC) method [3]. ARC with the correct thickness have been commonly used to reduce both reflectance and transmittance. The ARC ranging refractive index causes a difference between the various layers, which causes a decrease in reflectance [4]. As a result, reflection occurs whenever the refractive index (RI) of 2 materials varies as shown in **Figure 1**. The bigger the deviation of incident light from equilibrium, the higher the light reflection will be. The ARC is commonly used on semiconductor technology where there is an issue on light reflection [5]. One of most difficult aspect of developing a PV device is reaching the absolute maximum of energy conversion efficiency, which could be obtained by semiconductor and advanced material micro-fabrication [5].

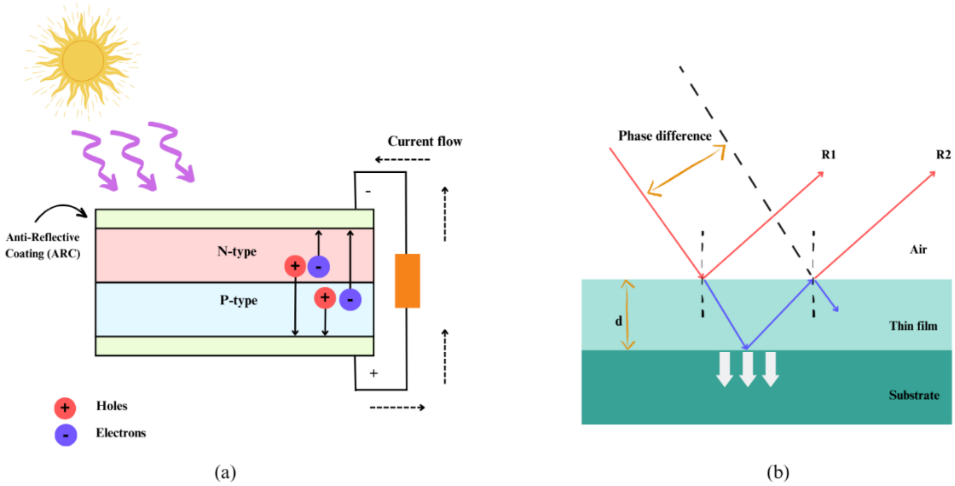

Figure 1 The illustration of (a) structure of solar cell with ARC (b) a schematic of the diffusion of light in single layer thin films [6].

In optics, anti-reflective coatings (ARC) have been considered to be the most fundamental thin film used. Multiple benefits of the coatings include enhanced transmissibility, reduced glare, and minimised surface reflection. A wide range of equipment, including solar energy systems, lenses, displays, cameras, spyglasses, and lasers, use the thin antireflective film [7]. This is due to the fact that ARC can aid in improving and enhancing the efficient use of solar cells.

There are a number of forms of ARC that can be applied in solar cell simulation study, including single layer ARC (SLARC), double or bilayer ARC, triple layers of ARC, and occasionally up to 4 or 5 layers of ARC, for evaluating the effectiveness of silicon solar cells. Common materials used for SLARC are SiO_2, MgF_2, TiO_2, ZnO and many more materials that are fitted to be used in the study. For bilayer ARC, there are some materials used such as MgF_2/SiO_2, Al_2O_3/TiO_2 and MgF_2/ZnS, and for triple ARC, some example materials used are $MgF_2/Al_2O_3/ZnS$ and GaInP/GaAs/Ge.

The thickness of each layer must be meticulously monitored in order to provide the optimum anti-reflective effect, that is the minimal reflectance, so that destructive interference occurs at the required or desired wavelength [8]. The efficiency of solar cells is dependent upon an effective ARC as it guarantees a high photocurrent while reducing reflection [9]. Many researchers have taken advantage of several ARCs since the development of solar cells, and they continue to search for an ideal ARC that is able to be used to enhance the performance of solar cells. The refractive index of ARC can be calculated with below Eq. (1) [11]:

$$\eta_{arc} = \sqrt{\eta_{air} \times \eta_{arc}(\lambda_0)} \quad (1)$$

Considering one of the prerequisites for perfect anti-reflection coatings, antireflection coatings should span a wide wavelength spectrum, including the Ultraviolet (UV) region [10]. The thickness of the ARC material [11] that leads to the smallest amount of reflection can be calculated using the following Eq. (2).

$$d = \frac{\lambda_0}{4 \times \eta_{arc}} \quad (2)$$

where η_{arc} is the refractive index of ARC and η_{air} is the refractive index of an ARC for a certain wavelength(λ_0). A more comprehensive examination of Eq. (1) demonstrates that the refractive index of ARC is affected by both the refractive index of air and the wavelength-dependent refractive index of a specific anti-reflection coating [11].

The PN Junction Solar cells are semiconductors that transform sunlight into electricity. These are also referred to as photovoltaic cells (PV). Solar panels are composed of a number of components known as solar cells which have been manufactured separately and depending on the required power, the solar panels are built up in both parallel and series [12].

In a solar cell, a P-N junction splits the electron and hole carriers to generate a voltage and actual work as shown in **Figure 2**. There really are several other techniques that could be implemented to remove carriers from a solar cell, such as metal-insulator-semiconductor or even carrier-selective contacts [13]. A photon with an energy larger than the bandgap of a semiconductor material that from the p-n junction is constructed, is required for a solar cell to generate electricity.

The electrons in the valence band capture this photon then flowing from there into the conduction band where they can generate an electrical current. Photons with an energy of at least 1.12 eV are necessary for silicon with an effective bandgap of 1.12 eV [14]. The energy can be converted into wavelength or frequency by Eq. (3) [14] below:

$$E(eV)\,\frac{1.240}{\lambda\,(nm)} \tag{3}$$

where E is the energy in electron volt (eV) and λ is the wavelength in nanometer (nm). For silicon, the wavelength was set to be about 1,107 nm and the electromagnetic or waves with the wavelength of 1,107 nm or lower will take part towards a great performance of electron-hole pair generation [14].

Snell's law explains the degree of refraction and the relationship between the angle of incidence, angle of refraction, and refractive index between 2 mediums. Light refracts or bends when it travels from 1 medium to another hence, the law of refraction makes it possible to foresee the amount of bending [15]. Below is Eq. (4) that showed the basic formula of Snell's Law:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_1}{n_2} \tag{4}$$

n_1 and n_2 are the indexes of refraction for the 2 mediums, and θ_1 and θ_2 are the angles of incidence and refraction formed by the ray at the point of intersection perpendicular to the normal. Whenever a light ray penetrates a material with a higher index of refraction than the material that emerges when it departs, the direction it travels is bent towards the normal [16].

The performance of solar cells can be evaluated using the solar cell conversion efficiency. The output power of the solar cell to solar radiation input power is expressed as a ratio [10]. Solar cell efficiency (maximum), η_{max} is calculated by using below Eq. (5):

$$\eta_{max} = \frac{P_{max}}{E * A_c} \times 100\ \% \tag{5}$$

where η represents the efficiency of solar cell, P_{max} indicates maximum power output (W), *E* is the incident radiation flux (Wm^{-2}) and A_c is the area of collector (m^2). P_{in} is the incident radiation power density which can be determined from Eq. (6) below:

$$P_{in} = I_{light} \times A \tag{6}$$

where I_{light} is the amount of incident light intensity, which is equivalent to 0.1 Wcm^{-2} for AM 1.5 radiation, and A is the surface area of the solar cell [10]. The fill factor of standard commercial solar cells is higher than 0.70 [17]. The fill factor (*FF*) of the silicon solar cell was calculated by using the formula as stated in Eq. (7) below:

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} \tag{7}$$

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

This had been established that all the different types of anti-reflective coatings differed from one another in many ways, yet each of them possessed an identical reason, that is to decrease reflection with the goal to further enhance the efficiency of the solar cell. As a result, this paper will demonstrate precisely why anti-reflective coatings are crucial in silicon solar cells as well as how single layer of different types of ARC materials may improve the effectiveness of solar cells.

Simulation procedure

In this research, Personal Computer One Dimensional or known as PC1D was used in the simulation of anti-reflective coating of the solar cell where it enables 1-dimensional simulation of the behavior of photovoltaic systems based on semiconductors [18]. Of the publicly accessible solar cell modelling software, PC1D is the one software that is most frequently used. Its successfulness is the outcome of its efficiency, user-friendly design, and continuous updates to the newest cell models. It can be utilized to simulate the functionality of freshly developed technologies and to support new users learn about the physics of the equipment [19].

With this PCID files, it also comes with numerous parameters of the crystalline semi conductors that can be used in the solar technology such as gallium arsenide (GaAs), silicon (Si), indium phosphate (InP), germanium (Ge), AlGaAs and InGaAs. Solar spectrum mainly AM0 and AM 1.5 also available in this software. Hence, this is why PCID is one of the software that was easy and user friendly when it comes to photovoltaic research due to its usefulness.

A certain amount of nodes are produced to be solved once the user begins setting up the fundamental PC1D model. Within the regions of the cell where the doping alters and close to surfaces, the number of nodes increases. It is also feasible to pause the simulation programme while analysing the device's geographic distribution of carriers or field at a specific bias point [19]. By using this software, researchers can get various types of desired outputs such as current density, base current and power, diffusion length, doping density, quantum efficiency and much more [20].

For this study, as shown in **Table 1**, the basic parameters choosen where the devicea area was set to 110 cm^2 and exterior front reflectance was set to 10 %. The thickness for Region 1 was kept constant to 10 µm and Region 2 was 100 µm and the materials choose was silicon for both regions. N-type and P-type background doping was set to 1×10^{18} and 1×10^{17} cm^{-3}, respectively. In the EXCITATION region, the parameters choosen from the excitation mode was transient and it automatically set 16 timesteps. The constant intensity was set to 0.1 Wcm^{-1} and the solar spectrum was AM1.5. The ARC materials were applied in the exterior front reflectance which is under 'Device' one if the parameters displays in the PC1D. Below is the table that indicates the parameters of the solar cell using PC1D simulation software.

Table 1 Solar cell parameters using PC1D software.

Parameter	Value	Reference
Device		
Device area	110 cm^2	
Surface texturing	None	
Surface charge	None	
Exterior front reflectance	10 %	[18]
Exterior rear reflectance	None	
Internal optical reflectance	None	
Emitter contact		
Base contact		
Region 1		
Thickness	10 µm	
Material	Silicon	
Dielectric constant	11.9	
Band gap	1.124 eV	
Intrinsic concentration	1×10^{10} cm^{-3}	[18]
Refractive index	Fixed	
Absorption coefficient	Enabled	
Free carrier absorption	Enabled	

Parameter	Value	Reference
N-type background doping	1×10^{18} cm^{-3}	[11]
Bulk recommendation	1,000 µs	[18]
Region 2		
Thickness	100 µm	
Material	Silicon	
Dielectric constant	11.9	
Band gap	1.124 eV	
Intrinsic concentration	1×10^{10} cm^{-3}	[18]
Refractive index	Fixed	
Absorption coefficient	Enabled	
Free carrier absorption	Enabled	
P-type background doping	1×10^{17} cm^{-3}	[11]
Bulk recommendation	1,000 µs	[18]
Excitation		
Excitation mode	Transient,16 timesteps	
Temperature	25 °C	
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	

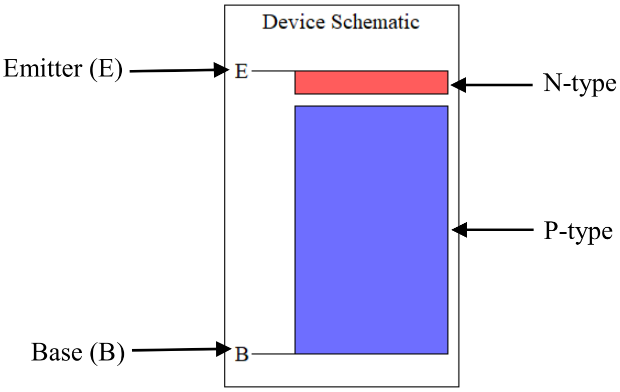

Figure 2 The device schematic of solar cell using PC1D software.

Figure 2 above displays the structure that was set to be the main structure for the simulation of solar cell using PC1D and the schematic device of solar cell. The red region is the area for N-type and the E represents the emitter while the blue region is the area for P-type and the B is for base. The steps of simulation of single layer ARC in silicon solar cell are illustrated as shown in **Figure 3** below.

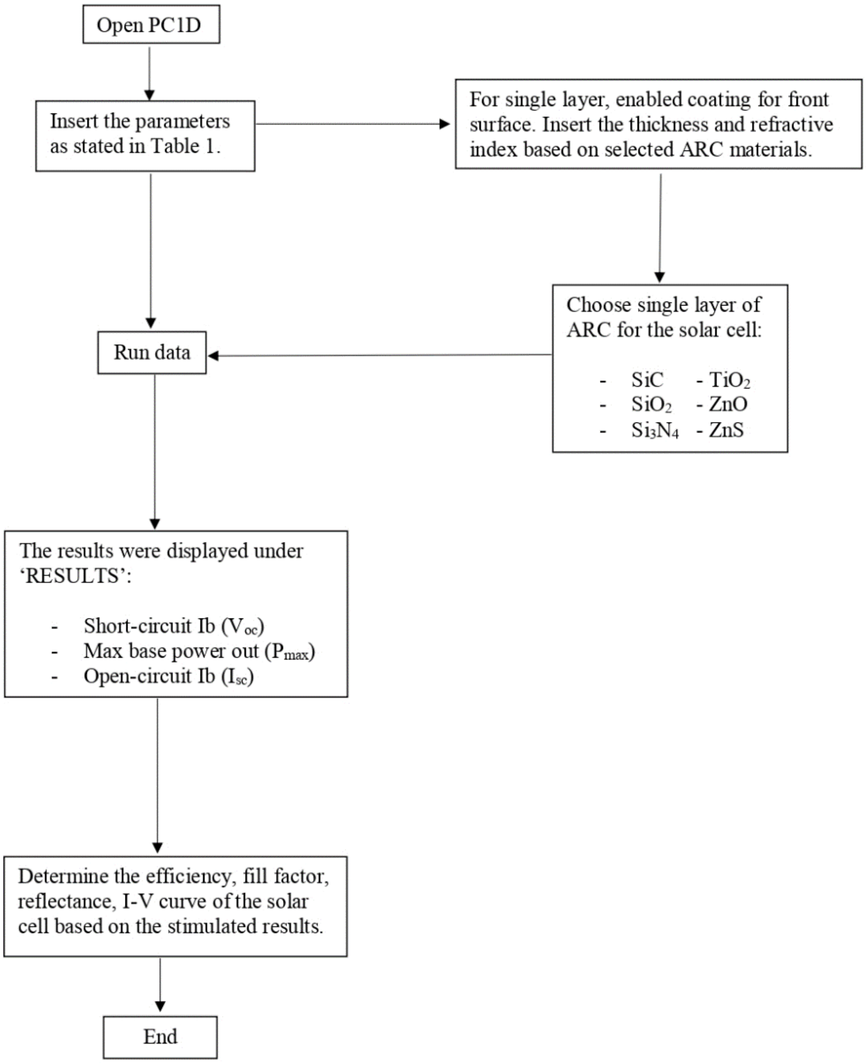

Figure 3 Flow chart of simulation steps of single layer ARC.

Results and discussion

PC1D software was used to stimulate a silicon solar cell without an anti-reflective coating, and the results are presented in **Table 2**. The stimulated results which consists of open circuit voltage (V_{oc}), maximum power output (P_{max}), short circuit current (I_{sc}), efficiency (η) and fill factor (*FF*) was illustrated in **Table 1**. Hence, this finding indicated that our study succeeded in improving the efficiency of the structured solar cell compared to other researchers' results of the same efficiency value within the same range of data.

Table 2 Data of simulation without ARC.

P_{in}	**Open circuit output (P_{max})**	**Maximum power voltage (V_{oc})**	**Short circuit current (I_{sc})**	**Fill factor (*FF*)**	**Efficiency (η)**
0.1 Wcm^{-2}×110 cm^2	3.707 V	2.335 W	0.7374 A	0.8542	21.23 %

Table 2 explained the results of PC1D simulation when the solar was not applied with any anti-reflective coating. The results for V_{oc}, P_{max} and I_{sc} were 3.707 V, 2.335 W and 0.7374 A, respectively. Hence, based on those data, the efficiency of the simulation without ARC was only 21.23 % with the fill factor of 0.854203. **Figure 4** shows the *I-V* curve of silicon solar cell without ARC.

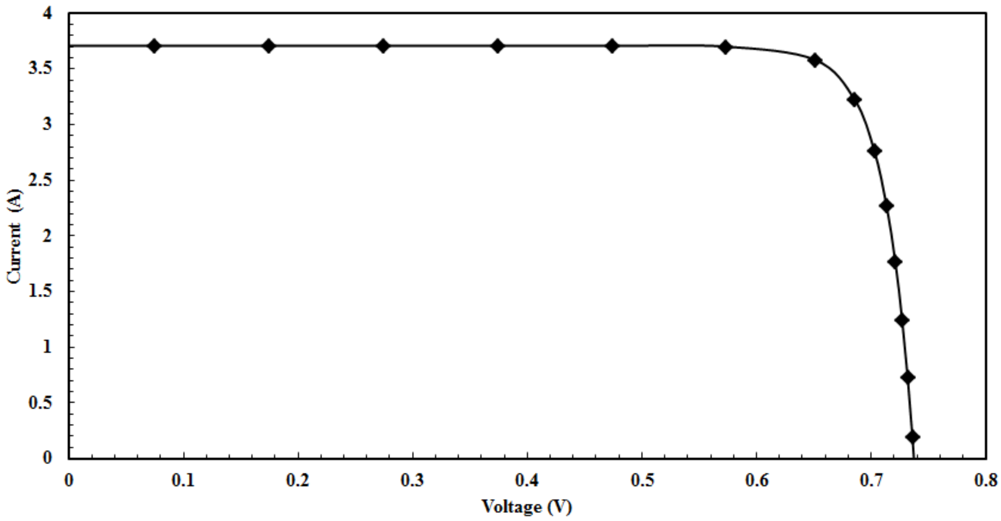

Figure 4 *I-V* curve of silicon solar cell.

The *I-V* curve is the graph of output voltage vs current at various degrees of insolation and temperature and able to show the capability of a PV cell or panel to convert sunlight into energy that can potentially be determined by studying those curves. Based on the graph of **Figure 3**, it showed that the current is constant at highest point between the voltage ranging from –0.1 to 0.5 V however, the points for current starts to declining drops after the voltage of 0.5 V until it almost reaches –0.5 A. When using anti-reflective coatings, the front surface optically coated option is the one selected in the simulation to add the ARC layer. The refractive index and thickness were thereafter modified in accordance with various ARCs. High surface recombination rates have been found to decrease short-circuit current thereby decreasing solar cell efficiency. The bonds that hang at the surface's top enable the photo-excited electron-hole pair to reassemble on the surface [11].

In this research, the different types of ARC layers used were SiC, SiO_2, Si_3N_4, TiO_2, ZnO and ZnS. Data of the different anti-reflective coatings used in PC1D were shown as **Table 2** below.

Table 3 Data of different types of ARC.

Types of ARC	λ (nm)	Refractive Index	Thickness (nm)	V_{oc} (V)	P_{max} (W)	I_{sc} (A)	Fill Factor (*FF*)	Efficiency (ŋ)
Silicon carbide (SiC) ARC	250	3.25	19.231	2.85	1.76	0.7306	0.8453	16 %
	300	3.528	21.259	2.844	1.756	0.7306	0.8451	15.96 %
	400	3.519	28.417	2.953	1.837	0.7315	0.8504	16.7 %
	500	3.457	36.159	3.015	1.881	0.7321	0.8522	17.1 %
	600	3.406	44.04	3.01	1.878	0.732	0.8524	17.07 %
	700	3.358	52.114	2.979	1.856	0.7318	0.8514	16.87 %
	800	3.315	60.332	2.938	1.826	0.7314	0.8498	16.6 %
	900	3.285	68.493	2.901	1.799	0.7311	0.8482	16.35 %
	1,000	3.247	76.994	2.898	1.797	0.7311	0.8482	16.34 %
	1,100	3.228	85.192	2.914	1.809	0.7312	0.8490	16.45 %
	1,200	3.2	93.75	2.926	1.818	0.7313	0.8496	16.53 %

Types of ARC	λ (nm)	Refractive Index	Thickness (nm)	V_{oc} (V)	P_{max} (W)	I_{sc} (A)	Fill Factor (*FF*)	Efficiency (ŋ)
Silicon dioxide (SiO_2) ARC	250	1.52	41.12	2.961	1.842	0.7316	0.8503	16.75 %
	300	1.51	49.67	3.083	1.927	0.7326	0.8532	17.52 %
	400	1.5	66.67	3.328	2.075	0.7345	0.8489	18.86 %
	500	1.482	84.35	3.484	2.181	0.7357	0.8509	19.83 %
	600	1.48	101.351	3.545	2.225	0.7361	0.8527	20.23 %
	700	1.474	118.72	3.507	2.198	0.7358	0.8518	19.98 %
	800	1.473	135.78	3.416	2.127	0.7352	0.8469	19.34 %
	900	1.472	152.85	3.302	2.06	0.7343	0.8496	18.73 %
	1,000	1.471	169.95	3.198	1.999	0.7335	0.8522	18.17 %
	1,100	1.47	187.07	3.116	1.948	0.7329	0.8530	17.71 %
	1,200	1.469	204.22	3.059	1.911	0.7324	0.8530	17.37 %
Silicon nitride (Si_3N_4) ARC	250	2.289	27.304	3.013	1.879	0.732	0.8520	17.08 %
	300	2.167	34.61	3.182	1.989	0.7334	0.8523	18.08 %
	400	2.07	48.31	3.515	2.204	0.7359	0.8521	20.04 %
	500	2.03	61.576	3.729	2.348	0.7374	0.8539	21.35 %
	600	2.02	74.257	3.79	2.386	0.7378	0.8533	21.69 %
	700	2.003	87.369	3.736	2.353	0.7374	0.8541	21.39 %
	800	1.996	100.2	3.61	2.271	0.7366	0.8540	20.65 %
	900	1.991	113	3.463	2.166	0.7355	0.8504	19.69 %
	1,000	1.987	125.82	3.335	2.079	0.7346	0.8486	18.9 %
	1,100	1.985	138.54	3.243	2.026	0.7339	0.8512	18.42 %
	1,200	1.983	151.28	3.18	1.988	0.7334	0.8524	18.0 7%
Titanium dioxide (TiO_2) ARC	250	2.46	25.407	2.995	1.867	0.7319	0.8517	16.97 %
	300	3.326	22.55	2.912	1.807	0.7312	0.8487	16.43 %
	400	2.68	37.213	3.365	2.097	0.7348	0.8481	19.06 %
	500	2.48	50.403	3.61	2.271	0.7366	0.8540	20.65 %
	600	2.404	62.396	3.677	2.316	0.737	0.8546	21.05 %
	700	2.364	74.027	3.63	2.285	0.7367	0.8545	20.77 %
	800	2.341	85.434	3.517	2.205	0.7359	0.8520	20.05 %
	900	2.325	96.774	3.387	2.11	0.735	0.8476	19.18 %
	1,000	2.313	108.085	3.28	2.047	0.7342	0.8500	18.61 %
	1,100	2.305	119.306	3.209	2.005	0.7336	0.8517	18.23 %
	1,200	2.298	130.548	3.159	1.975	0.7332	0.8527	17.95 %

Types of ARC	λ (nm)	Refractive Index	Thickness (nm)	V_{oc} (V)	P_{max} (W)	I_{sc} (A)	Fill Factor (*FF*)	Efficiency (ŋ)
Zinc oxide (ZnO) ARC	250	2.388	26.173	3.003	1.873	0.732	0.8521	17.03 %
	300	2.404	31.198	3.155	1.973	0.7332	0.8529	17.94 %
	400	2.114	47.304	3.513	2.202	0.7359	0.8518	20.02 %
	500	1.968	63.516	3.728	2.348	0.7374	0.8541	21.35 %
	600	1.913	78.411	3.788	2.384	0.7378	0.8530	21.67 %
	700	1.883	92.937	3.733	2.351	0.7374	0.8541	21.37 %
	800	1.864	107.296	3.609	2.27	0.7366	0.8539	20.64 %
	900	1.851	121.556	3.461	2.164	0.7355	0.8501	19.67 %
	1,000	1.841	135.8	3.331	2.077	0.7346	0.8488	18.88 %
	1,100	1.833	150.027	3.235	2.021	0.7338	0.8514	18.37 %
	1,200	1.826	164.294	3.168	1.981	0.7333	0.8527	18.01 %
Zinc sulphate (ZnS) ARC	250	2.6	24.038	2.976	1.854	0.7317	0.8514	16.85 %
	300	2.57	29.183	3.124	1.954	0.7329	0.8534	17.76 %
	400	2.56	39.063	3.413	2.125	0.7352	0.8469	19.32 %
	500	2.421	51.632	3.636	2.288	0.7367	0.8542	20.8 %
	600	2.363	63.479	3.696	2.328	0.7372	0.8544	21.16 %
	700	2.332	75.043	3.645	2.294	0.7368	0.8542	20.85 %
	800	2.324	86.059	3.524	2.21	0.736	0.8521	20.09 %
	900	2.31	97.403	3.392	2.113	0.735	0.8475	19.21 %
	1,000	2.301	107.648	3.291	2.054	0.7343	0.8500	18.67 %
	1,100	2.296	119.774	3.21	2.006	0.7336	0.8519	18.24 %
	1,200	2.29	131.004	3.16	1.976	0.7332	0.8529	17.96 %

Based on the data on **Table 3**, it was shown that different types of ARC have different results of V_{oc}, P_{max} and I_{sc}, fill factor and efficiency due to the wavelength and thickness applied on the ARC. It can be seen that Si_3N_4 has the highest efficiency which is 21.69 % among the other ARC at the wavelength of 600 nm, followed by the 2nd highest, ZnO which has efficiency of 21.67 %, where there is very little difference between Si_3N_4 and ZnO. Then, ZnS has the efficiency of 21.16 % and next with the efficiency 21.05 % is the TiO_2 and then comes SiO_2 with the efficiency of 20.23 %. Last but not least, with the lowest efficiency among the other ARC based on the simulation is SiC, with the efficiency of 17.07 %. This is due to the decrease in light reflection which is the factor that renders this effectiveness enhance achievable [21]. This data was almost equivalent and can be supported by Hashmi *et al.* [11].

Si_3N_4 exhibits the highest value of efficiency at the wavelength of 600 nm along the range of 250 nm to 1,200 nm compared to other materials is because between those range of wavelengths indicates the visible light or AM1.5 spectra in the solar radiation spectrum and according with the UCAR COMET Programme, approximately 43 % of the sun's radiant energy resides in the visible region of the spectrum. This is the total amount of energy from the sun incorporated over wavelengths that range from 400 to 700 nm [22]. Hence, this explained why the optimum value of efficiency occurs at the wavelength of 600 nm along the range of 250 to 1,200 nm.

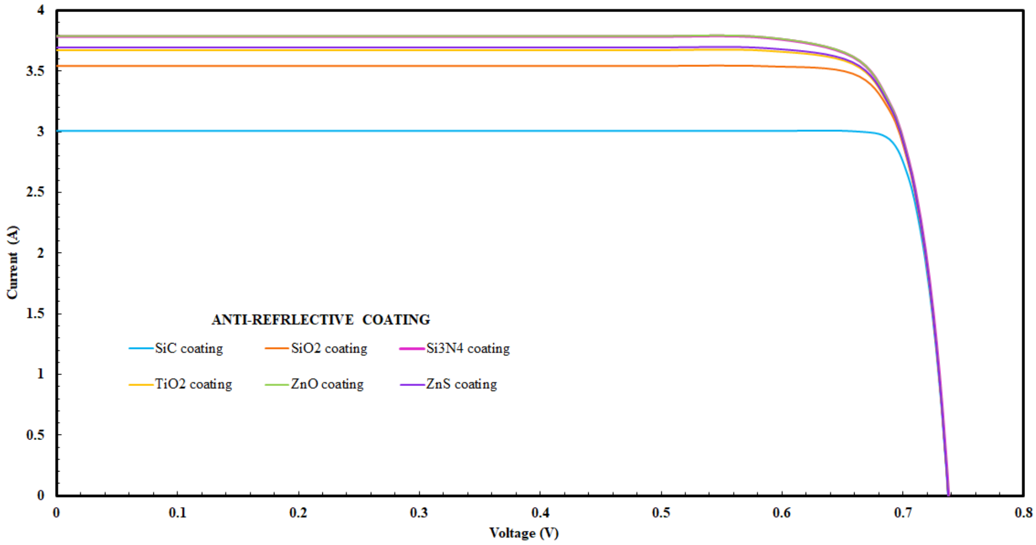

Figure 5 *I-V* curve of silicon solar cell with different ARC.

Figure 5 above indicates the *I-V* curve of silicon solar with different ARC upon the using of PC1D. The curve with SiC coating has the lowest relationship of current and voltage, followed by SiO_2, TiO_2, ZnS, ZnO and lastly, Si_3N_4 which has the highest number of relationships between current and voltage.

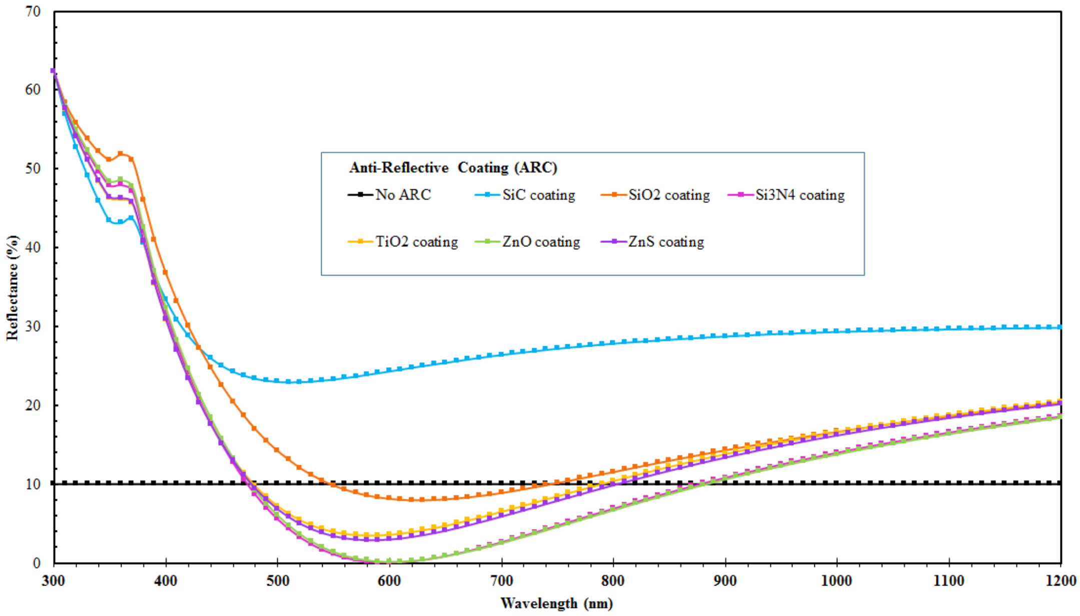

Figure 6 Reflectance curves of different ARC.

Figure 6 explained the reflectance curves of different ARC based on the simulation. It is shown that all ARC except for SiC, represent by the light blue curve, has the lowest reflectance at the wavelength of 600nm while the pink curve, which is Si_3N_4 coating has the lowest reflectance which is the 0.03 %, among the other ARC with the efficiency of 21.69 %. Then, followed by the 2nd lowest reflectance (0.14 %) that is the green curve which represents ZnO coating, that has little difference of efficiency compared to Si3N4 which is 21.67 %. After that, comes ZnS and TiO_2 coating which reflected 2.98 % and 3.59 % respectively. The black curve which represents silicon solar cell without ARC shows constant reflectance of 10 % from the wavelength of 300 to 1,200 nm.

This is due to the fact that SiC coating has the highest reflectance which it reflected up to 24.31 % compared to Si_3N_4. It is reasonable to hypothesize that the optimized ARC thickness is possibly linked to the development of an adequate refractive index with a low extinction coefficient and a notable reduction in reflection, which leads to a high level of light absorption and the extraction of charge on the front surface [23]. It is intriguing that the wavelength and related thickness for which the ARC is intended display the lowest reflectivity [11]. The decrease is undoubtedly related to the absorption band, and the increase might have been caused by high reflectance. In addition, the absorption and extinction coefficients vary slightly with thickness of the ARC [11].

Apart from the band-edge, absorption is particularly strong for high energy photons (lower wavelengths). As a result, nearly every high energy photon is absorbed within possible cell thicknesses where light trapping techniques are inefficient. However, towards the band edge, the absorption coefficients become significantly lower, indicating that it is within this narrow bandwidth where light-trapping becomes important and crucial [24]. Hence, this can be surmise that the lower the reflectance, the higher efficiency of the solar cell. Furthermore, the results obtained are reliable and supported by Hashmi *et al.* [11].

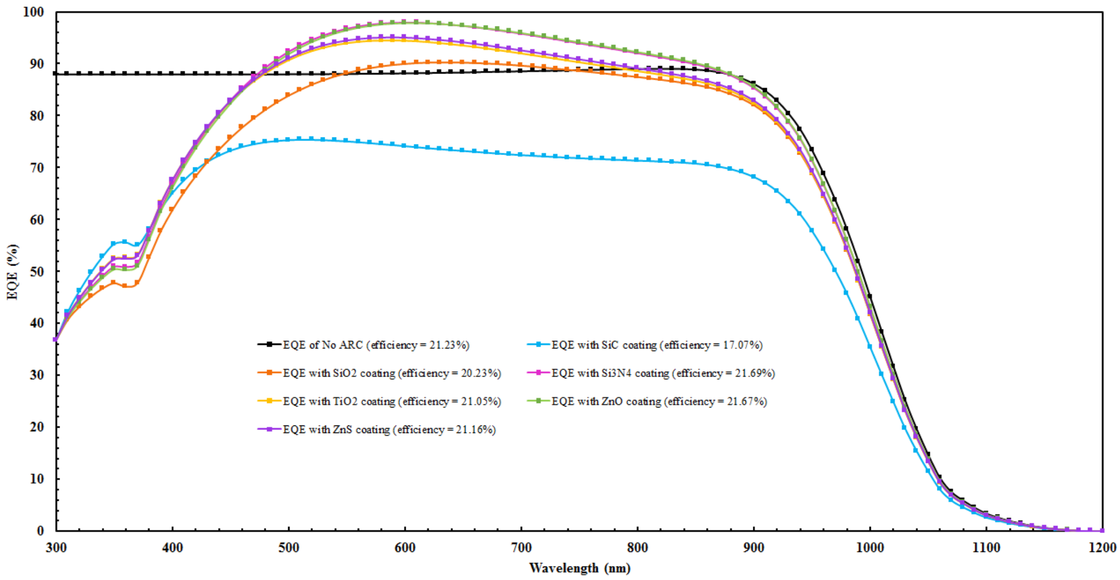

Figure 7 External quantum efficiency (EQE) of different ARC.

Based on **Figure 7**, it can be explained that SiC coating which represents by the blue curve has the lowest EQE between the wavelength of 450 to 1,000 nm. Different with Si_3N_4 coating which represents by the pink curve, with the highest efficiency of 21.69 %, rises the highest at the wavelength between 400 to 1,000 nm. Contrast to the black curve which is said to be the solar cell without ARC, the curve only constant which did not have any improvement along the wavelength of 300 to 1,000 nm.

This is due to the fact that SiC has the highest reflectance hence, causing the coating has to display the lowest efficiency. Also, it is adequate enough to point out that the decrease in reflection within the AR coatings serves as the surface passivation lowers the amount of dangling bonds in solar cells, hence minimizing the recombination impacts and enhancing the overall EQE of the solar cell [11]. This can be explained by the fact that the ARC layers enhance the passivation process improving overall EQE by lowering recombination on the surface at the interface [27]. Through the addition of an ARC layer, the EQE was extremely boosted. This effect may have been attributed to the ARC layer's reduced reflection of the solar spectrum. This reason was supported by Kc *et al.* [23] and the data also almost equal to the results obtained by Hashmi *et al.* [11].

Also, it can be explained that based on its properties, Si_3N_4 exhibits the highest EQE due to the fact Si_3N_4 is a common nitride-based compound and given its relatively easy production and affordable cost of raw materials, this material is an excellent potential material for possible uses in the solid-state lighting field [25]. Besides Si_3N_4, ZnO also comes close as the 2nd highest EQE because ZnO possesses a refractive index close to 2, a broad optical bandgap in the range of 3.3 to 3.7 eV, is readily apparent in the area of visible light, and has strong adhesion and hardness making ZnO is a particularly promising for anti-reflection coating of silicon solar cells [26]. The properties described for both Si_3N_4 and ZnO make it that these 2 materials are ideal and suitable for anti-reflective coating of silicon solar cell.

Conclusions

The designing and modelling of silicon solar cell with different materials of single layer of anti-reflective coating (ARC) were successfully manufactured using PC1D software. The simulation efficiency can be further boosted even more by adjusting the thickness and other attributes of the ARC materials. Optical characteristics of the solar cell were studied within the 600 nm wavelength area at optimum reflection condition. Based on the simulation, it was concluded that Si_3N_4 has the highest efficiency which is 21.69 % compared to other ARC with the lowest reflection. With the thickness of 74.257 nm and refractive index of 2.02, Si_3N_4 generates open circuit voltage (V_{oc}) of 3.79V, open circuit current (I_{sc}) of 0.7378 with maximum power (P_{max}) of 2.386, and also, the value of fill factor (*FF*) of 0.853281989. In addition, Si_3N_4 exhibits highest external quantum efficiency (EQE) among the different ARC, making this particular kind of material standing out even more. The assortment of ARC materials implemented in this study assists in providing recommendations as well as data regarding which materials have the greatest potential for application on silicon solar cells. Hence, to be concluded, Si_3N_4 is the best ARC materials that could be applied on solar cell to enhance the efficiency performance of the solar cell. This matter encompasses needed to be studied more widely and thoroughly since the findings and results could assist further studies to discover the most ideal materials that can be used as an anti-reflective coating that will enhance the efficiency of silicon solar cells more significantly.

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