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Enhancing silicon solar cell efficiency with double layer antireflection coating

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Abstract: Antireflection coating on silicon, a high refractive index substrate, was theoretically investigated. The effects of antireflection coating on electrical parameters such as the short circuit current, open circuit voltage, maximum current density, maximum voltage, maximum power, power density, and conversion efficiency of the solar cell were simulated. Various previous works in which solar cell efficiencies were investigated after applying double layer antireflection coating (DLARC) were reviewed. Ti_2O_3 and MgF_2 were then applied in a DLARC design, taking into consideration the refractive index dispersion of the two materials. The results were compared with other works in the solar spectral range (400–1200 nm). As a result of simulation, the reflectance on the surface was reduced from 30.2% to 2.37%. Moreover, about 22% conversion efficiency and 38.6 mA/cm^2 short circuit current density were achieved for a silicon cell with DLARC. These results were compared with the parameters of a cell without coating, one with single layer coating, and one with zero reflectance on the front surface.

Key words: Antireflection coating, reflectance, external quantum efficiency, solar cell

1. Introduction

Antireflection coating (ARC) of surfaces is of great interest in many applications and in several research fields like optics and optoelectronics. The usual targets of applications range from military applications to display panels, solar cells, and optical lenses [1,2]. Antireflection layers are needed when two adjacent materials have different refractive indices, thus leading to unwanted Fresnel's reflections from their interfaces. The most common method to suppress the reflection is to coat the surface with a thin film having a suitable refractive index and an optimized thickness. However, it is well known that many factors, electrical or optical, limit solar cell efficiency. Enhancing the efficiency of a given solar cell could be approached by using a good cell design and trying to have minimum reflectance on its surface by using ARC techniques [3–5]. ARCs have become one of the key issues in the mass production of silicon solar cells. They are generally examined by a computer system prior to using them on the solar cell surface to ensure that they enhance the solar energy transmitted to the cell, thus increasing its efficiency. Many studies have shown that the performance of single layer coating does not satisfy these requirements due to its narrow band at minimum reflectance [5]. Double layer ARCs (DLARCs) [5–7] have better performance when referring to broadband solar cells. However, if one wants to achieve minimum reflectance of multiple wavelengths, additional layers must be added [8].

Dhungel et al. [9] used MgF_2/SiN_x ARC to enhance cell efficiency by 1.19 relative to its efficiency prior to coating. Lien et al. [10] applied double layer SiO_2/TiO_2 coating to enhance cell efficiency by 1.32 relative

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to its efficiency prior to coating. Bahrami et al. [11] considered double layer Al_2O_3/ TiO_2 ARC simulation to enhance cell efficiency by 1.41 relative to its efficiency prior to coating.

Here we present a design for single layer ARC (SLARC) and DLARC on silicon substrates. Ti_2O_3 and MgF_2 were applied to form DLARC used for silicon solar cells. In this design the dispersion of the refractive indices of the used materials was taken into consideration. Solar cell parameters such as the short circuit current, open circuit voltage, maximum current density, maximum voltage, maximum power, power density, and conversion efficiency of the cell were calculated. These parameters were compared before coating, after coating with a single layer, after coating with a double layer, and with zero reflectance of the cell surface. The results of the DLARC were comparable with those of the zero reflectance condition. The errors in calculating electrical cell parameters were discussed.

2. The matrix method in DLARC design

The ARC layer is a thin dielectric layer with a refractive index n and thickness t, designed to remove surface reflection via interference effects [12]. To design thin film applications, firstly the monitoring wavelength must be obtained for a silicon solar cell with a band gap of about 1.124 eV. At long wavelengths the ability of the semiconductor to absorb photons with energies below its band gap is limited. At short photon wavelengths each photon has a large energy; any energy above the band gap energy is not utilized by the solar cell and instead heats the solar cell. Increasing the cell temperature negatively affects cell performance, causing decreased energy conversion efficiency. Therefore, the best range for the cell is from 400 to 1100 nm [13]. The middle of the desired band is at around 700 nm; therefore, the coatings were designed to present minimum reflection around 700 nm. For this condition the ideal case for DLARC can be designed by calculating the appropriate refractive index and optimum thickness for each layer theoretically using the matrix method. The method of matrices has been considered an effective approach to the solution of Maxwell's equations in stratified media, where each single film is represented by a 2 $\times$ 2 matrix. Therefore, the assembly of a single film with a refractive index n_1 on a substrate with a refractive index n_s is represented as follows [12]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta & (i\ \sin\delta)/\eta \\ \eta(i\sin\delta) & \cos\delta \end{bmatrix} \begin{bmatrix} 1 \\ \eta_s \end{bmatrix}, \tag{1}$$

where η is the tilted optical admittance with components represented by:

$$\eta_{\perp\perp} = \sqrt{E_0/\mu_0} n\cos\theta$$

for the perpendicular component, and by:

$$\eta_{\|} = (\sqrt{E_0/\mu_0} n)/cos\theta$$

for the parallel component, where θ is the angle of propagation through the film, δ is the phase thickness of the film ($\delta = 2\pi nt\cos\theta/\lambda_0$, where t is the geometric thickness of the film and λ_0 is the monitoring wavelength), and η_s is the substrate admittance.

SLARC with single minimum reflectance is not enough; we can do better using different designs with multiple layers. DLARC for silicon solar cell surfaces was proved to be satisfactory [11]. Thus, it is possible to have a broadband almost at zero reflection in our region of interest (400–1100 nm). Extending the above analysis for the double layer case, the matrix representation for two layers is as follows:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & (i\ \sin\delta_1)/\eta_1 \\ \eta_1(i\sin\delta_1) & \cos\delta_1 \end{bmatrix} \begin{bmatrix} \cos\delta_2 & (i\ \sin\delta_2)/\eta_2 \\ \eta_2(i\sin\delta_2) & \cos\delta_2 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_s \end{bmatrix}. \tag{2}$$

This gives the amplitude reflection coefficient, r [12]:

$$r = \frac{m_{11}\eta_o + m_{12}\eta_o\eta_s - m_{21} - m_{22}\eta_s}{m_{11}\eta_o + m_{12}\eta_o\eta_s + m_{21} + m_{22}\eta_s}, \tag{3}$$

where $m_{11},\ m_{12}, m_{21},$ and m_{22} are the elements of the characteristic matrix resulting from multiplying the two matrices representing the two layers. For the ARC design the reflectance R = r. r* must be equated to zero. Considering the normal incidence on layers of quarter-wavelength optical thicknesses gives the following:

$$(\frac{\eta_2}{\eta_1})^2 = \frac{\eta_s}{\eta_0}, \tag{4}$$

where η_o is the admittance of the surrounding medium.

This condition determines the materials needed for the DLARC design. By analyzing this equation, it was found that the two chosen dielectric materials must satisfy the following condition: $\eta_2 > \eta_1$. In this design the available materials, which give the nearest satisfaction of Eq. (4), are Ti_2O_3 and MgF_2, respectively.

After determining the refractive indices of the suitable materials, the second step was to find the optimum thickness of each layer using Eq. (2). Thus, the reflectance for the assembly is given as follows:

$$R = \left[\frac{\eta_0 - Y}{\eta_0 + Y}\right]\left[\frac{\eta_0 - Y}{\eta_0 + Y}\right]^*, \tag{5}$$

where Y = C/B. The real and imaginary parts of this expression must be equated separately, giving the following [12]:

$$-(\eta_1\eta_s/\eta_2)\sin\delta_1\sin\delta_2 + \eta_s\cos\delta_1\cos\delta_2 = \eta_0 cos\delta_1\cos\delta_2 - (\eta_0\eta_2/\eta_1)\sin\delta_1\sin\delta_2$$

and

$$\eta_1\sin\delta_1\cos\delta_2 + \eta_2\sin\delta_2\cos\delta_1 = (\eta_0\eta_s/\eta_2)\sin\delta_2\cos\delta_1 + (\eta_0\eta_s/\eta_1)\sin\delta_1\cos\delta_2,$$

i.e.

$$\tan\delta_1\tan\delta_2 = \frac{(\eta_s - \eta_0)}{\left(\frac{\eta_1\eta_s}{\eta_2}\right) - \left(\frac{\eta_0\eta_2}{\eta_1}\right)}$$

and

$$\tan\delta_2/\tan\delta_1 = \eta_2[(\eta_0\eta_s - \eta_1^2)/[\eta_1(\eta_2^2 - \eta_0\eta_s)],$$

giving

$$(tan\delta_1)^2 = \frac{(\eta_s - \eta_0)\left(\eta_2^2 - \eta_0\eta_s\right)\eta_1^2}{(\eta_1^2\eta_s - \eta_0\eta_2^2)\left(\eta_0\eta_s - \eta_1^2\right)} \tag{6}$$

and

$$(tan\delta_2)^2 = \frac{(\eta_s - \eta_0)\left(\eta_0\eta_s - \eta_1^2\right)\eta_2^2}{(\eta_1^2\eta_s - \eta_0\eta_2^2)\left(\eta_2^2 - \eta_0\eta_s\right)}. \tag{7}$$

For solutions to exist, either all three of the following expressions: $\left(\eta_2^2 - \eta_0\eta_s\right)$, $[\left(\eta_0\eta_s - \eta_1^2\right)$, and $\left(\eta_1^2\eta_s - \eta_0\eta_2^2\right)]$, must be positive, or just one term of them must be positive. After obtaining the values for δ_1 and δ_2, the value that satisfies these equations must be chosen. The values of the geometrical thickness t_i can be obtained from the following equation:

$$t_i = \frac{\delta_i\lambda_0}{2\pi n_i}, \tag{8}$$

where i stands for 1 or 2 layers.

3. Application for single and double layers

Figure 1 shows the characteristic reflectance curve of the cell surface before any ARC and with a single layer of a quarter-wave thickness from SiO on a silicon solar cell surface. The layer details are shown in Table 1 as configurations. (Eq. (1)) The refractive index for the silicon substrate was 3.4 and the layer thickness was tuned to a wavelength with a high number of photons, which is appropriate for the semiconductor band gap at 700 nm. It can be seen from Figure 1 that the reflectance was minimized by only about one single wavelength across the whole wavelength range.

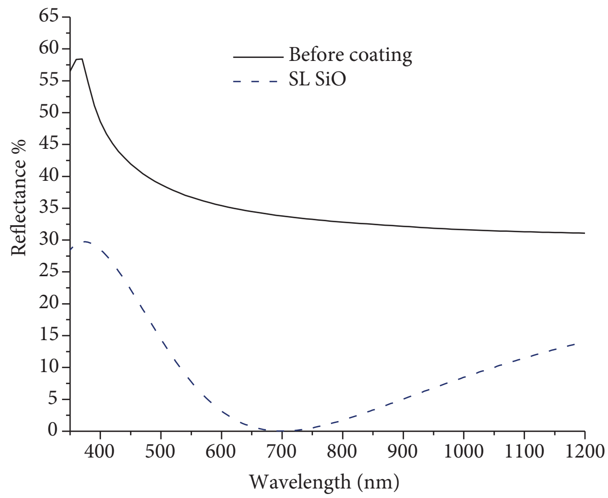

Figure 1. Cell surface reflectance before coating and with SLARC (*Air/SiO/Si*).

Table 1. Optical configurations of ARC single and double layer designs.

Configuration		n_1	n_2	t_1		t_2		λ_0 (nm)
1	Air/SiO/Si	1.875	—	93.31 nm	$1*\lambda_0/4$	—	—	700
2	Air/MgF_2/Ti_2O_3/Si	1.378	2.26	88.89 nm	$0.7*\lambda_0/4$	60.31 nm	$0.78*\lambda_0/4$	700

As we can see in Figure 1, there were a number of benefits of ARC for solar cells, even with the simple single layer design. The total reflectance was reduced on average from 30.4% to 7.5% in the wavelength range of 400–1100 nm. However, a higher reduction in the average surface reflection can be achieved by addressing the disadvantages of the single layer design. One disadvantage of SLARC is that a wider region of minimum reflectance cannot be attained without additional layers. Moreover, the materials suitable for use as thin films are limited in number and the designer has to use what is available. Therefore, in many applications we must use more layers to obtain specific refractive indices to achieve a wider band with almost zero reflectance by varying the thicknesses [12].

This problem can be solved by thinking in the ideal spectral range for solar cells (400–1100 nm). A design with a broadband minimum reflection in the mentioned range can be performed as follows: the monitoring wavelength is taken to be 700 nm, the material types are chosen using Eq. (4), and the thicknesses are calculated with Eq. (8). The design details of DLARC are shown as configurations Eq. (2) in Table 1. Figure 2 shows the resulting reflectance for a cell surface with DLARC (Air/MgF_2/Ti_2O_3/Si).

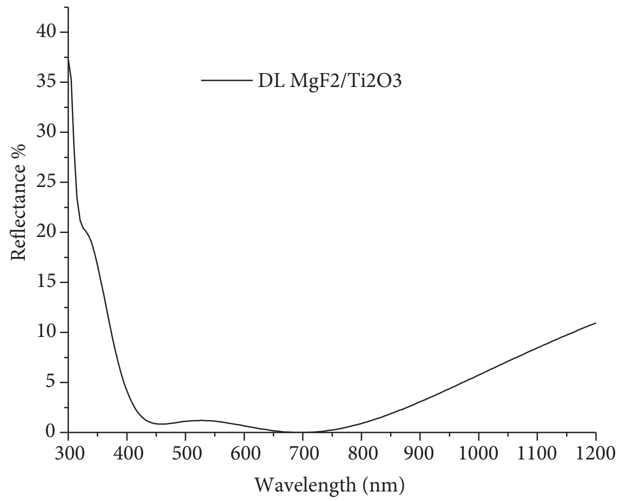

Figure 2. Cell surface reflectance with DLARC ($Air/MgF_2/Ti_2O_3/Si$).

As shown in Figure 2, a wide band at almost zero reflectance in the desired region of the solar spectrum was achieved by only two layers. To estimate how far this enhancement in the optical conditions affects some electrical parameters of the chosen cell, which is the goal, a brief definition of these electrical cell parameters is introduced in the next section.

4. Electrical parameters

4.1. Conversion efficiency

Enhancing the short circuit I_{sc} current and the maximum power P_m is vital for the production of a cell with good conversion efficiency. Conversion efficiency can be evaluated by the following equation [14]:

$$\xi = \frac{P_m}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}, \tag{9}$$

where V_{oc} is the open circuit voltage of the cell and P_{in} is the input power of the incident photons of sunlight. FF is the fill factor of the cell, which is a symbol of squareness of the current–voltage (I–V) curve and can be calculated by the following [15]:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}, \tag{10}$$

where V_m and I_m are the maximum voltage and the maximum current, respectively.

4.2. External quantum efficiency (EQE)

Quantum efficiency is defined as “the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on it”. The quantum efficiency may be given either as a function of the wavelength or as energy. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is unity. The quantum efficiency for photons with energy below the band gap is zero. Internal quantum efficiency refers to the efficiency with which photons that are not reflected or transmitted out of the cell can generate collectable carriers. However, it is often useful in the optical field to study the EQE because it includes the effects of optical losses such as transmission and reflection [16]. The EQE equation can be written as follows [16]:

$$EQE(\lambda) = \frac{hc}{q\lambda} * \frac{I_{sc}(\lambda)}{E(\lambda)}, \tag{11}$$

where $h$is the Planck's constant, $c$is the velocity of light in vacuum, $q$is the electron charge, $and\, E(\lambda)$ is the energy of each incident photon.

The EQE can be rewritten as follows:

$$EQE(\lambda) = \frac{hc}{q\lambda} SR(\lambda), \tag{12}$$

where SR is the spectral response of the cell surface, defined as "the ratio of the current generated by the solar cell to the power incident on the solar cell".

4.3. Simulation program for electrical cell parameters

Solar cell parameters before and after applying the ARC film on the front surface of the cell were studied using the PC1D software in simulation mode for solar cells [17]. The PC1D program contains files for the solar spectrum, mainly the AM0 and AM1.5 spectra. Furthermore, it contains files with parameters for semiconductors used in photovoltaic technology such as GaAS, a-Si, AlGaAs, Si, InP, and Ge. Silicon crystalline cells were chosen for simulation because they are the most popular semiconductors in the industry of photovoltaic cells. In fact, there are already two PC1D ready files that contain standard parameters to be used during the simulation of solar cells. The "one-sun.exc" file gives the short circuit current, open circuit voltage, and maximum power values. The "scan-qe.exc" file gives the characteristic reflectance curve versus the wavelength, the curve of the EQE versus the wavelength, and the curve of the internal quantum efficiency versus the wavelength.

To obtain these results, we had to set some parameters. First, we set the area of the cell to 148.6 cm^2 and the thickness to 250 μm, which is the typical thickness of a silicon wafer. For "p-type background doping", we set the P-type doping concentration level to 3 $\times$ e^{16} cm^{-3}, which defined a lightly doped p-Si substrate. To form a P-N junction, we set the "n-type"; the peak doping was set to 9 $\times$ e^{19} cm^{-3} and the depth factor was 0.11 μm. In this way we set up the n-type region near the surface of the silicon wafer. We illuminated the cell with 0.1 Watt/ cm^2 and chose "one-sun" from the file. The program allows ARC to be added in terms of thickness and refractive index as external files. This allowed us to use the dispersion relations and the matrix method in the design of ARC.

5. Simulation results and discussion

In the current paper two computer simulation programs were used to calculate the results. Firstly, for the optical part, a self-program was designed by our team to calculate the thickness of each layer and the reflection at each wavelength of the ARC design for the cell surface, taking into account the dispersion relations of the materials used. A modified Lorentz–Lorenz relation for the material dispersion was used because its results represent truly the refractive index dispersion of the used materials [18]:

$$n = \left[\frac{\lambda^8 + 2\left(A\lambda^8 + B\lambda^6 + C\lambda^4 + D\lambda^2 + E\right)}{\lambda^8 - \left(A\lambda^8 + B\lambda^6 + C\lambda^4 + D\lambda^2 + E\right)} \right]^{1/2}, \tag{13}$$

where A, B, C, D, and E are the material constants.

Secondly, for the electrical parameters to be evaluated, the PC1D program was used for its simplicity and accuracy [17]. An input power density of sunlight of 0.1 w/cm^2 was chosen to be the incident on the front surface of a silicon solar cell with 1.124 eV of band gap energy. This program accepts the reflectance as an external file, which gives the opportunity to link the optical and electrical programs together.

As a result of this enhancement in the optical parameter (reflectance), we expected good results in the electrical parameters. The I–V curves of the solar cell without ARC, at zero reflectance, and with SL (SiO) and DL (MgF_2/Ti_2O_3) ARCs are presented in Figure 3, which shows that the structure of the ARC changes the short circuit current due to the increment of effective photon absorption of incident light. Thus, a significant improvement of the short circuit current after ARC was observed. The enhancement of the electrical results here were due to the optical design. Moreover, a very high current, almost the optimum current (the current when surface reflectance is zero), was obtained. Indeed, a very good energy conversion was achieved, which matched that of the cell with zero reflectance.

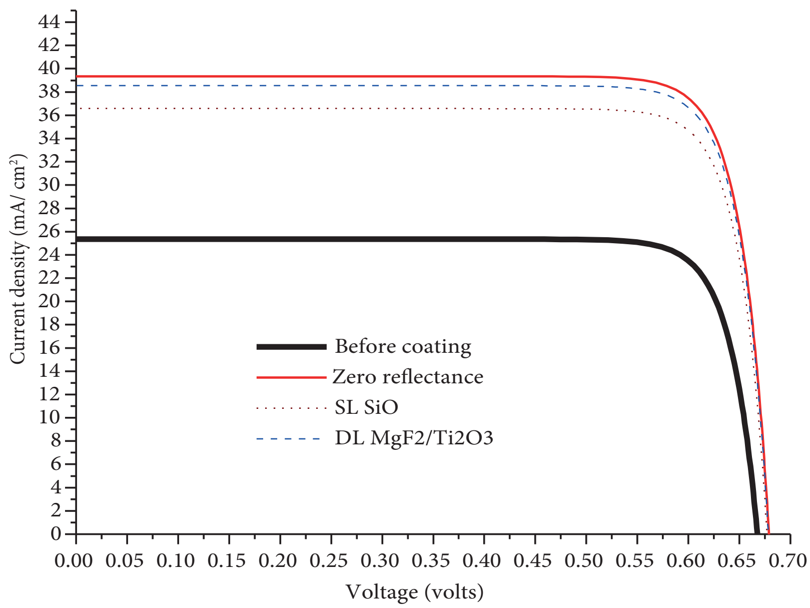

Figure 3. The I–V characteristic curve for the cell with: no ARC, zero reflectance, SLARC (*Air/SiO/Si*), and DLARC ($Air/MgF_2/Ti_2O_3/Si$).

The short circuit current, open circuit voltage, maximum current, maximum voltage, maximum power, fill factor, power conversion efficiency, and relative power conversion efficiency (relative to no ARC) of the solar cell in terms of the mentioned conditions of ARC are presented in Table 2.

The performance of ARC can be carefully studied in terms of reflectance and EQE. The EQE is an image of reflectance: as the reflectance goes to 0, the EQE goes to 100%. The EQE shows how much the reflectance affects the output current. Thus, quantum efficiency is the most important factor; it is a recombination between the optical parameter (reflectance) and electrical parameters (short circuit I_{sc} and conversion efficiency), while all of these parameters are enhanced by the ARC design. The EQEs of a cell in the cases of no ARC, zero reflectance, SLARC, and DLARC are shown in Figure 4, where the effects of ARC on EQE can be observed. The cell with DLARC was the best; it was nearly identical to the ideal optical case (the cell with zero reflectance on the surface).

Table 2. Simulation of electrical parameters characterizing the silicon solar cell with no ARC, zero reflectance, SLARC, and DLARC.

ARC design	No ARC	Zero reflectance	Single layer SiO	DL MgF_2/Ti_2O_3
$I_{sc}(mA/cm^2)$	25.35	39.35	36.57	38.60
$V_{oc}(volts)$	0.67	0.68	0.68	0.68
$I_m(mA/cm^2)$	24.37	37.78	35.20	37.00
$V_m(volts)$	0.58	0.60	0.59	0.60
$P_m(Watt)$	2.11	3.34	3.10	3.28
$\sigma_m(mWatt/cm^2)$	14.23	22.50	20.85	21.91
FF	0.84	0.84	0.84	0.84
$\xi\%$	14.23	22.25	20.85	21.91
ξ/ξ_0	1	1.56	1.47	1.54

Figure 5 shows the power densities of the solar cell before coating, with zero reflectance, with SLARC, and with DLARC. It should be noted that the power density increased to about 1.58, 1.46, and 1.54 for the zero reflectance, the SLARC, and the DLARC, respectively, as measured with respect to a cell without ARC.

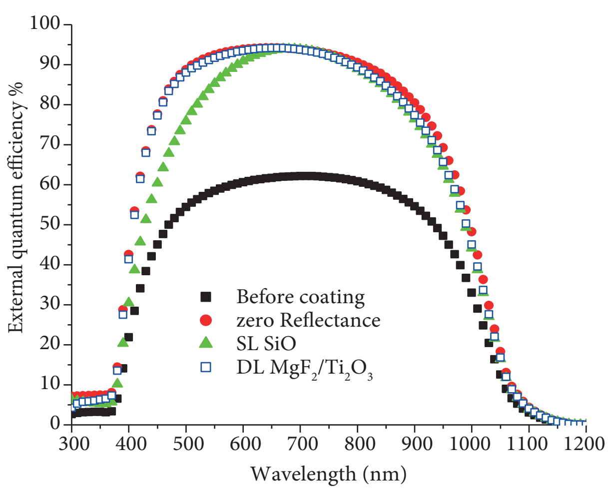

Figure 4. External quantum efficiency of the cell with: no ARC, zero reflectance, SLARC *(Air/SiO/Si)*, and DLARC $(Air/MgF_2/Ti_2O_3/Si)$.

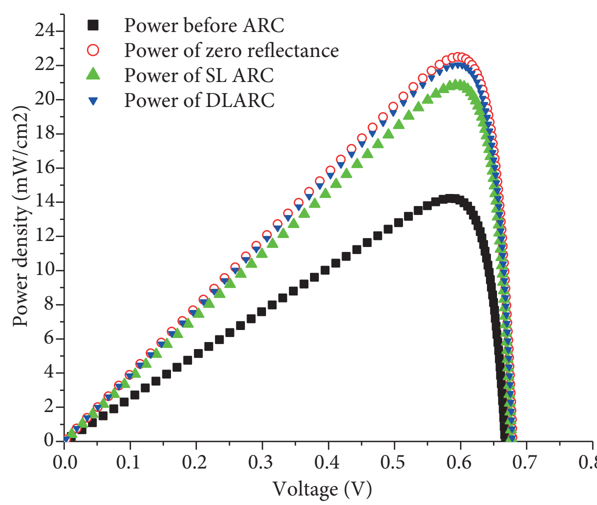

Figure 5. Power density for cells before coating, with zero reflectance, SLARC, and DLARC.

6. Errors of simulation

Errors were added to the layer thickness and the refractive index in order to estimate the total errors of the simulation's optical and electrical parameters. An error of $\pm 5\%$ in the layer thickness and an error of $\pm 5\%$ in the layer refractive index were added and the studied parameters were recalculated.

Table 3 shows the errors in the average reflectance for SLARC and DLARC following the addition and subtraction of errors of 5% in thickness and 5% in the refractive index. The resulting maximum error in the average reflectance was in the first decimal digit.

Tables 4 and 5 show the errors in the cell electrical parameters for SLARC and DLARC following the addition and subtraction of errors of 5% in thickness and 5% in the refractive index. Some electrical parameters did not change, while others changed in the first decimal digit.

Table 3. Errors in the average reflectance for single and double ARC layers due to errors in thickness and the refractive index.

ARC design	Errors for average reflectance				
	Without error	Error +5% n	Error –5% n	Error +5% th	Error –5% th
SL	7.50	7.78	7.57	7.78	7.38
DL	2.37	2.34	2.72	2.01	2.89

n: refractive index; th: thickness.

Table 4. Errors in electrical parameters for SLARC due to errors in thickness and the refractive index.

Parameters	Errors for SLARC				
	Without error	Error +5% n	Error –5% n	Error +5% th	Error –5% th
$I_{sc}(mA/cm^2)$	36.57	36.45	36.55	36.37	36.70
$V_{oc}(volts)$	0.68	0.68	0.68	0.68	0.68
$I_m(mA/cm^2)$	35.20	34.71	35.19	35.10	35.26
$V_m(volts)$	0.59	0.60	0.59	0.59	0.59
$P_m(Watt)$	3.10	3.09	3.10	3.08	3.11
$\sigma_m(mWatt/cm^2)$	20.85	20.77	20.83	20.73	20.92
FF	0.84	0.84	0.84	0.84	0.84
$\xi\%$	20.85	20.77	20.83	20.73	20.92
ξ/ξ_0	1.47	1.46	1.47	1.46	1.47

n: refractive index; th: thickness.

Table 5. Errors in electrical parameters for DLARC due to errors in thickness and the refractive index.

Parameters	Errors for DLARC				
	Without error	Error +5% n	Error –5% n	Error +5% th	Error –5% th
$I_{sc}(mA/cm^2)$	38.59	38.61	38.61	38.65	38.49
$V_{oc}(volts)$	0.68	0.68	0.68	0.68	0.68
$I_m(mA/cm^2)$	37.00	37.01	37.42	37.02	36.95
$V_m(volts)$	0.60	0.60	0.59	0.60	0.59
$P_m(Watt)$	3.28	3.28	3.28	3.28	3.27
$\sigma_m(mWatt/cm^2)$	22.05	22.06	22.06	22.08	21.96
FF	0.84	0.84	0.84	0.84	0.84
$\xi\%$	22.05	22.06	22.06	22.08	21.99
ξ/ξ_0	1.55	1.55	1.55	1.55	1.55

n: refractive index; th: thickness.

7. Conclusion

In the present work, the silicon solar cell was investigated in the cases of SLARC and DLARC on the front surface of the cell. Single layer coating showed the ideal point that gave the maximum power conversion efficiency. The available material with a refractive index near the optimum case of SLARC was SiO. However, DLARC had almost maximum power conversion efficiency at a wider spectral range. Simulation results for the two layers showed an improvement with the MgF_2/Ti_2O_3 double layer coating at a monitoring wavelength of 700 nm and thicknesses of 0.7 and 0.78 multiple of $\lambda/4$ for the two materials, respectively. Moreover, it was deduced that a wider low reflection band produced a higher value of the short circuit current of the cell. As a result, the quantum efficiency of the cell was almost identical to the ideal case (the cell with zero reflectance on the surface). An exact dispersion equation for the refractive index of the used materials is very important for good results. The present work can serve as a useful reference for future work in highly efficient and selective wavelength solar cells [19,20].

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