

Theoretical Study of the Electrical Performance of a Silicon Solar Cell Coated with Anti-Reflective Layers: Current-Voltage Characteristic and Power

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Abstract

This paper presents a theoretical study of the electrical performance of a silicon solar cell coated with anti-reflective layers (MgF_2 , SiO_2 , ZrO_2 and TiO_2). Building on the reduction in optical reflection achieved by these coatings, established in a companion study, this work focuses on their impact on the cell's current-voltage characteristic and power output. Analysis of the current-voltage characteristics revealed that the ZrO_2 -coated cell exhibits the highest short-circuit current density, with an improvement of approximately 47 per cent compared with bare silicon. Furthermore, an analysis of the power output from the cell showed that the maximum power increased from 198.89 mW/cm^2 for bare silicon to 298.78 mW/cm^2 for the ZrO_2 -coated cell, representing an improvement of approximately 50.22 per cent. Consequently, silicon solar cells equipped with an anti-reflective coating, particularly one made of ZrO_2 , offer considerable potential for improving the electrical performance of solar cells.

Keywords

Silicon, Anti-Reflective Coating, Photocurrent, I-V Characteristic, Power

1. Introduction

The share of photovoltaic energy within the renewable energy mix keeps expand-

ing, spurred by the ongoing effort to reduce reliance on fossil fuels [1]. Among the various routes to harnessing sunlight, photovoltaic (PV) electricity generation has drawn substantial research attention because it combines environmental, economic and efficiency advantages [2]. Within a PV generation system, the module remains the core production unit [3], and its output is ultimately governed by the solar cells that convert sunlight into electricity [4]. Owing to its abundance and to a now-mature fabrication technology, silicon remains the material of choice for solar cells, accounting for more than 90 per cent of the world market on account of its low cost and stability [1]–[3]. Bare silicon nevertheless suffers from a well-known shortcoming: a large fraction of the incoming radiation is reflected at its surface rather than absorbed, which caps the cell's conversion efficiency. Already apparent at the time of the first silicon photocell developed by Chapin *et al.* [5], this drawback has motivated an extensive body of work on anti-reflective coatings as a means of curbing optical losses [6]. Progress in materials science and device physics has, over recent years, steadily pushed up the photoelectric conversion efficiency achievable with such cells [7]. Coating the cell surface with an anti-reflective layer remains the most widely used remedy: by exploiting optical interference, it lowers reflectance and increases the share of radiation absorbed by the active material, thereby raising the amount of light converted into current [8]. Sun *et al.* [9], for instance, compared several anti-reflective materials for their effect on photon absorption, external quantum efficiency and photoelectric conversion efficiency, and found that a SiNx layer with a refractive index of 2.0 combines good chemical stability with effective reflectance reduction over a broad spectral range [10]. Comparable gains in optical absorption have been reported for amorphous silicon cells [11], while device modelling has clarified the electro-optical mechanisms at play [12]. Since the anti-reflective material, its refractive index and its thickness all govern how effective this reduction is, a detailed theoretical treatment of their influence on cell performance is warranted. Other approaches to reducing reflection losses, such as plasmonic nanostructures (Ag, Au, Al), pursue the same goal and have been reported to raise conversion efficiency by up to 6.58 per cent [13]. It is in this context that a companion study established, for a silicon cell coated with MgF₂, SiO₂, ZrO₂ or TiO₂, the resulting reduction in reflectance and the associated gain in external quantum efficiency. Building directly on those optical results, the present paper turns to the electrical consequences of the same anti-reflective coatings: after recalling the photocurrent model used to relate the reduced reflectance to the short-circuit current, the influence of the coating material, its refractive index and its thickness on the cell's current-voltage characteristic and power output is examined and compared with the performance of the uncoated cell.

2. Theoretical

2.1. Refractive Index of Silicon

The refractive index of silicon, calculated using Sellmeier's equation, varies with

wavelength as shown in **Table 1**:

$$n(\lambda) = \sqrt{A + \frac{B\lambda^2}{\lambda^2 - C}} \quad (1)$$

with $A = 9.825$, $B = 3.165$, $C = 0.1460 \times 10^{-12} \mu\text{m}^2$.

Table 1. Variation in the refractive index of silicon as a function of wavelength.

λ (nm)	399.90	427.50	459.90	495.90	539.00	590.40	652.50	729.30	826.50
n	5.570	4.961	4.583	4.320	4.123	3.969	3.847	3.752	3.673

2.2. Reflectance Coefficient of Bare Silicon

At normal incidence, the reflection coefficient R of bare silicon is given by:

$$R = \left(\frac{1 - n_2}{1 + n_2} \right)^2 \quad (2)$$

where n_2 is the refractive index of silicon.

2.3. Optimal Refractive Index of the Anti-Reflective Coating

The anti-reflection coating, of refractive index n_2 , matches the refractive indices between air (n_1) and silicon (n_3) in order to create destructive interference between the waves reflected at the two interfaces, thereby minimising reflection [10]. This condition is achieved for a quarter-wave thickness

$$e = \frac{\lambda}{4n_2} \quad (3)$$

for which the two reflected waves are in phase opposition. Requiring in addition that the reflected field be zero (equal amplitudes) leads to the relation $n_2 = \sqrt{n_1 n_3}$.

For $\lambda_{ref} = 800$ nm, where $n_3 \approx 3.75$ (Equation (1)) and $n_1 = 1$, the optimal index is

$$n_{2,opt} = \sqrt{1 \times 3.75} \approx 1.9365 \quad (4)$$

The materials studied (MgF_2 , SiO_2 , ZrO_2 , TiO_2) were selected for their refractive indices close to this value and their low absorption (**Table 2**). The choice of transparent, low-absorption materials deposited on silicon is a key criterion, as illustrated by the hole-transport layers studied for the recombination junction of perovskite/silicon, whose measured optical bandgaps (ranging from 1.61 to 3.57 eV depending on the material) directly determine the optical transmission to the active layer [14]. Furthermore, the thermal stability of dielectric stacks, such as that reported for $\text{Al}_2\text{O}_3/\text{SiON}$ structures intended for the passivation of crystalline silicon cells [15], as well as the microstructural and optical characterisation of silicon-oxygen-nitrogen films produced by plasma-assisted atomic layer deposition [16], are important factors to consider for the durability of anti-reflective coatings.

Table 2. Optimal thicknesses for different materials [17].

Materials for the anti-reflective coating	MgF ₂	SiO ₂	ZrO ₂	TiO ₂
sizes (nm) for $\lambda = 400$ nm	72	64	44	35
sizes (nm) for $\lambda = 800$ nm	145	130	92	79

2.4. The Effect of Anti-Reflective Coatings on the Reflection of Silicon

Where an anti-reflective coating is present, the reflectance coefficient results from multiple interference between the air/coating and coating/silicon interfaces:

$$r = r_{12} + \frac{t_{12}r_{23}t_{21}e^{j\varphi}}{1 - r_{23}r_{21}e^{j\varphi}}, \quad \varphi = \frac{4\pi}{\lambda}n_2e \quad (5)$$

where r_{12} , r_{21} , r_{23} , t_{12} , t_{21} are the Fresnel coefficients at the interfaces in question, and e is the thickness of the layer.

Table 3. Refractive indices of selected materials [18]-[20].

Material	MgF ₂	SiO ₂	ZrO ₂	TiO ₂
Index n (800 nm - 400 nm)	1.3751 - 1.3839	1.5383 - 1.5597	2.1816 - 2.2741	2.5198 - 2.20

The dispersion of the refractive index of each coating is taken into account: **Table 3** gives the values at 800 nm and at 400 nm, which are those used in the calculations and in the sensitivity analysis of Section 3 (for ZrO₂, n decreases from 2.27 at 400 nm to 2.18 at 800 nm). The corresponding quarter-wave thicknesses (Equation (3)) are those of **Table 3**. All four coatings are treated as non-absorbing between 400 and 800 nm (extinction coefficient $k = 0$), so that the index n_2 entering Equation (5) is real.

These values are consistent with those reported for the influence of SiNx:H and SiOx films on the optical and electrical properties of anti-reflective coatings applied to silicon solar cells [21].

2.5. Photocurrent and External Quantum Efficiency

In this study, the calculations are carried out on the assumption that the transport of excess minority carriers occurs solely in the direction perpendicular to the junction, which allows the results to be expressed in one-dimensional space. This assumption is realistic insofar as the lateral dimensions of the cell are much greater than its thickness. The external quantum yield is thus calculated using a one dimensional model shown in **Figure 1**:

$X_j = He$, W , $X - X_j = Hb$ and $X = H$ are, respectively, the thicknesses of the emitter, the space charge region, the base and the cell. The origin of the x-axis is taken inside the space charge region; the electric field is assumed to be practically zero in the two quasi-neutral regions; and the cell is under constant bias.

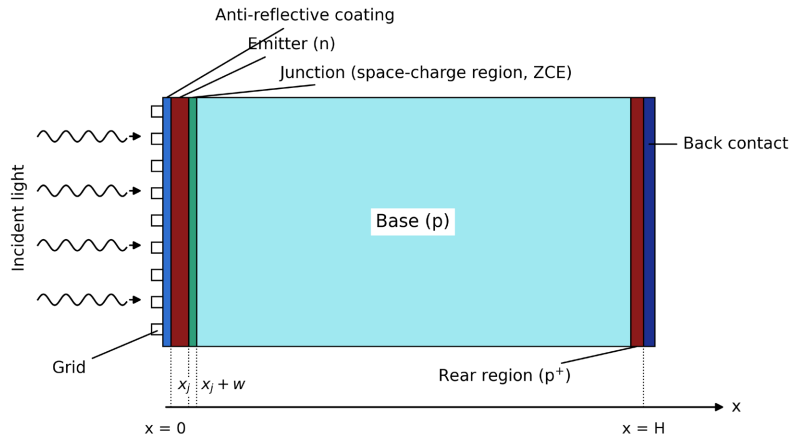


Figure 1. One-dimensional photovoltaic cell model.

For a non-equilibrium situation, the general one-dimensional transport equation for electrons in the p-region is given by:

$$\frac{\partial(n_p - n_{p0})}{\partial t} = D_n \frac{\partial^2(n_p - n_{p0})}{\partial x^2} + \mu_n E(x) \frac{\partial(n_p - n_{p0})}{\partial x} + \mu_n (n_p - n_{p0}) \frac{\partial E(x)}{\partial x} - \frac{n_p - n_{p0}}{\tau_n} + G_n(x) \quad (6)$$

and, for the holes in zone n:

$$\frac{\partial(p_n - p_{n0})}{\partial t} = D_p \frac{\partial^2(p_n - p_{n0})}{\partial x^2} + \mu_p E(x) \frac{\partial(p_n - p_{n0})}{\partial x} + \mu_p (p_n - p_{n0}) \frac{\partial E(x)}{\partial x} - \frac{p_n - p_{n0}}{\tau_p} + G_p(x) \quad (7)$$

where $(n_p - n_{p0})$ and $(p_n - p_{n0})$ are the excess minority carrier densities in the p- and n-regions, D_n and D_p are the diffusion coefficients, μ_n and μ_p are the mobilities, $E(x)$ is the electric field, τ_n and τ_p are the lifetimes, n_{p0} and p_{n0} are the equilibrium densities, and G_n and G_p are the generation rates of electrons and holes.

Considering the case where one of the materials is more heavily doped, these equations decouple by neglecting the term $\partial E / \partial x$ as well as the electric field in the quasi-neutral regions. In steady state, the continuity equations in the base and emitter are written respectively as:

$$D_n \frac{d^2(n_p - n_{p0})}{dx^2} + \alpha F(1 - R)e^{-\alpha x} - \frac{n_p - n_{p0}}{\tau_n} = 0 \quad (8)$$

$$D_p \frac{d^2(p_n - p_{n0})}{dx^2} - \frac{p_n - p_{n0}}{\tau_n} + G(\lambda) = 0 \quad (9)$$

These two second-order differential equations have the following general solutions:

$$n_p - n_{p0} = \frac{\alpha F(\lambda)(1 - R(\lambda))\tau_n}{\alpha^2 L_n^2 - 1} e^{\alpha(x_j - w)} \times A \quad (10)$$

with

$$A = \cosh\left(\frac{X - X_j - W}{L_n}\right) - e^{-\alpha(X - X_j - W)} \left\{ \frac{\frac{S_n L_n}{D_n} \left(\cosh \frac{H}{L_n} - e^{-\alpha H} \right) + \alpha L_n e^{-\alpha H}}{\frac{S_n L_n}{D_n} \sinh \frac{H}{L_n} + \cosh \frac{H}{L_n}} \right\} \sinh\left(\frac{X - X_j - W}{L_n}\right)$$

$$p_n - p_{n0} = \frac{\alpha F (1-R) \tau_n}{\alpha^2 L_p^2 - 1} \left\{ \frac{\left(\frac{S_p L_p}{D_p} + \alpha L_p \right) \sinh \frac{X_j - X}{L_p} + \left(\frac{S_p L_p}{D_p} \sinh \frac{X}{L_p} + \cosh \frac{X}{L_p} \right) e^{-\alpha X_j}}{\frac{S_p L_p}{D_p} \sinh \frac{X_j}{L_p}} - e^{-\alpha X} \right\} \quad (11)$$

The external quantum efficiency is derived from the photocurrent density using the following formula:

$$SR(RQE) = \frac{J_{ph}}{qF(\lambda)} \quad (12)$$

where J_{ph} represents the short-circuit photocurrent density. This density is given, in the emitter, the base and the space-charge region respectively, by:

$$J_{e_{ph}} = \frac{qF(1-R)\alpha L_p}{\alpha^2 L_n^2 - 1} \left\{ \frac{S_p L_p}{D_n} + \alpha L_p - \frac{\frac{S_p L_p}{D_p} \cosh \frac{X_j}{L_p} + \sinh \frac{X}{L_p} e^{-\alpha X}}{\frac{S_p L_p}{D_p} \sinh \frac{X_j}{L_p} + \cosh \frac{X_j}{L_p}} - \alpha L_p (-\alpha X) \right\} \quad (13)$$

$$J_{n_{ph}} = \frac{qF(1-R)\alpha L_n}{\alpha^2 L_n^2 - 1} e^{-\alpha(X_j + W)} \left\{ \alpha L_n - \frac{S_n L_n}{D_n} \frac{\cosh \frac{He}{L_n} - e^{-\alpha He} + \sinh \frac{He}{L_n} + \alpha L_n e^{-\alpha He}}{\frac{S_n L_n}{D_n} \sinh \frac{He}{L_n} + \cosh \frac{He}{L_n}} \right\} \quad (14)$$

$$J_{ZCE} = qF(1-R)[1 - e^{-\alpha W}]e^{-X_j} \quad (15)$$

Thus, the total external quantum efficiency resulting from the contribution of the various regions of the cell is given by: $SR = SR_b + SR_e + SR_{ZCE}$

where:

$$SR_b = \frac{(1-R)\alpha_n L_n}{\alpha_n^2 L_n^2 - 1} e^{-\alpha_n(X_j + W)} \frac{S_n L_n}{D_n} \frac{\cosh \frac{Hb}{L_n} - e^{-\alpha Hb} + \sinh \frac{Hb}{L_n} + \alpha L_n e^{-\alpha Hb}}{\frac{S_n L_n}{D_n} \sinh \frac{Hb}{L_n} + \cosh \frac{Hb}{L_n}} \quad (16)$$

$$SR_e = \frac{(1-R)\alpha_p L_p}{\alpha_p^2 L_p^2 - 1} \left\{ \frac{\frac{S_p L_p}{D_p} + \alpha_p L_p - e^{-\alpha_p X_j} \left(\frac{S_p L_p}{D_p} \cosh \frac{X_j}{L_p} + \sinh \frac{X_j}{L_p} \right)}{\frac{S_p L_p}{D_p} \sinh \frac{X_j}{L_p} + \cosh \frac{X_j}{L_p}} - \alpha_p L_p e^{-\alpha_p X_j} \right\} \quad (17)$$

$$SR_{ZCE} = (1 - R) \left[1 - e^{-\alpha W} \right] e^{-X_j} \quad (18)$$

The total photocurrent density is the sum of the densities of the three regions (P-N-ZCE) of the photovoltaic cell (Jain and Verma, 2013) [22]:

$$J_{ph} = J_n + J_p + J_{zce} \quad (19)$$

The total photocurrent J_{Total} is obtained by integrating the photocurrent density J_{ph} over the entire range of the solar spectrum used; J_{Total} is given by:

$$J_{Total} = \int_{\lambda_{min}}^{\lambda_{max}} J_{ph} \cdot d\lambda \quad (20)$$

In these expressions, $F(\lambda)$ is the incident spectral photon flux density, expressed in photons $\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{nm}^{-1}$ and obtained from the spectral irradiance $E(\lambda)$ ($\text{W} \cdot \text{cm}^{-2} \cdot \text{nm}^{-1}$) of the incident solar spectrum by $F(\lambda) = \lambda E(\lambda) / (hc)$. The photocurrent density $J_{ph}(\lambda)$ is therefore a spectral quantity ($\text{mA} \cdot \text{cm}^{-2} \cdot \text{nm}^{-1}$) and J_{Total} is expressed in mA/cm^2 . The reflectance $R(\lambda)$ of the bare and coated cells and the external quantum efficiency used in Equations (13)-(20) are those established in the companion optical study.

2.6. Current-Voltage Characteristic and Power of the Solar Cell

Under illumination, the current density delivered by the cell at a voltage V is described by the ideal single-diode model (a current source in parallel with a diode, without parasitic resistances):

$$J(V) = J_{Total} - J_0 \left[\exp \left(\frac{qV}{n_d kT} \right) - 1 \right] \quad (21)$$

where J_{Total} is the photogenerated current density given by Equation (20), J_0 the saturation current density of the junction, n_d the diode ideality factor, k the Boltzmann constant, T the temperature. The series resistance is taken as zero and the shunt resistance as infinite. The short-circuit current density is $J_{sc} = J(0) = J_{Total}$ and the open-circuit voltage is

$$V_{oc} = \frac{n_d kT}{q} \ln \left(\frac{J_{Total}}{J_0} + 1 \right) \quad (22)$$

The power density delivered by the cell is

$$P(V) = J(V) \cdot V \quad (23)$$

and is at its maximum $P_m = J_m \cdot V_m$ at the operating point where $dP/dV = 0$. The calculations were carried out with Mathcad.

3. Results

3.1. I-V Characteristic of a Bare Monocrystalline Silicon Solar Cell

Figure 2 shows the variation in current density of a bare monocrystalline silicon solar cell as a function of voltage. It can be seen that at zero voltage, the current density reaches a value of $480 \text{ mA}/\text{cm}^2$, corresponding to the short-circuit current density J_{sc} . This current density remains almost constant between 0 and 0.4 V, then decreases rapidly to reach $0 \text{ mA}/\text{cm}^2$ at about 0.53 V (open-circuit voltage).

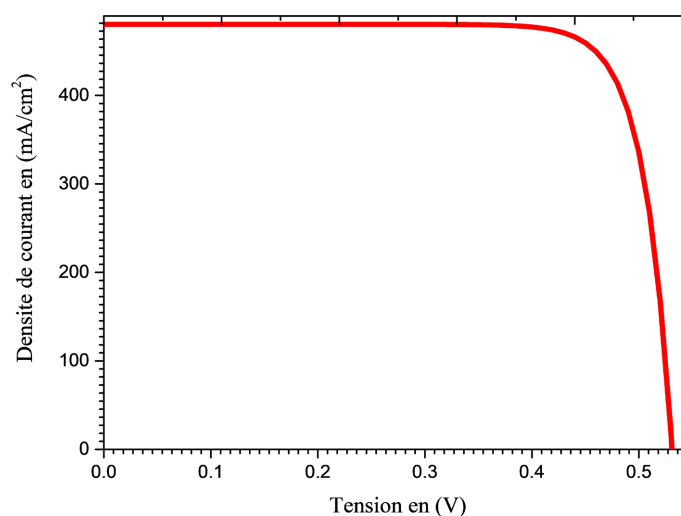


Figure 2. I-V characteristic of a bare monocrystalline silicon cell.

3.2. Study of the I-V Characteristics of a Silicon Solar Cell Coated with an Anti-Reflective Monolayer

Figure 3 shows the variation in current density as a function of voltage. It can be seen that, at zero voltage, the cell coated with ZrO_2 has a current density of around 705.7 mA/cm^2 , corresponding to the short-circuit current density. In contrast, those coated with TiO_2 , SiO_2 or MgF_2 have short-circuit current densities of approximately 667.1 mA/cm^2 , 682.3 mA/cm^2 and 641.93 mA/cm^2 respectively. It can be seen that the cell coated with ZrO_2 has a higher short-circuit current density than the other cells. This difference can be explained by the fact that the refractive index of ZrO_2 is closer to the optimal refractive index. Subsequently, the current densities of the various cells remain constant between 0 and 0.4 V. They then decrease rapidly, reaching 0 near the open-circuit voltage.

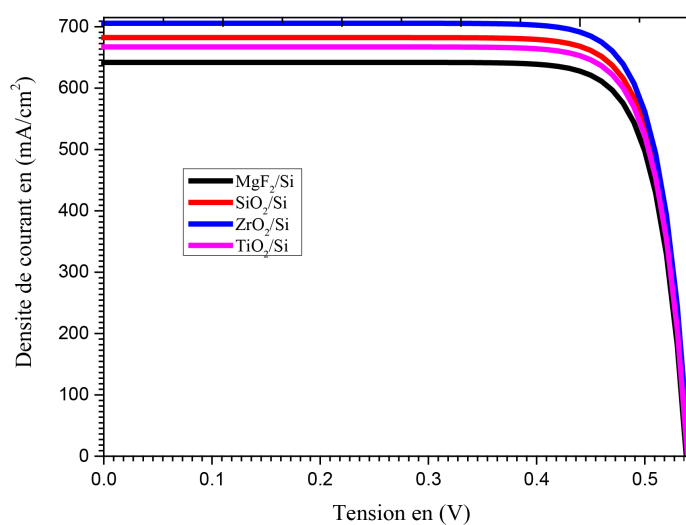


Figure 3. I-V characteristics of solar cells coated with different anti-reflective layers.

Short-circuit current densities, albeit of lower magnitude, have also been reported when a second anti-reflective layer was added on top of an already optimised monolayer [23]. These multilayer architectures, first explored in early work on multilayer silicon solar cells [24], were subsequently refined through graded refractive index designs, enabling further optimisation of reflection reduction across a broad spectral band [25].

3.3. Effect of the Refractive Index of the Anti-Reflective Coating (ZrO_2) on the I-V Characteristic

Figure 4 shows the variation in current density as a function of voltage. The values considered, from $n = 2.18$ to $n = 2.27$, span the dispersion of the ZrO_2 index between 800 nm and 400 nm (Table 2). We can see that for $n = 2.18$, the short-circuit current density is of the order of 705.7 mA/cm^2 , whereas for $n = 2.27$ it is of the order of 697.6 mA/cm^2 . This shows that the higher the refractive index, the lower the short-circuit current density. In other words, the greater the difference between the refractive index and the optimal index, the lower the short-circuit current density. Indeed, by increasing the refractive index of the anti-reflective layer, the condition for destructive interference is no longer met, thereby leading to a decrease in the current density.

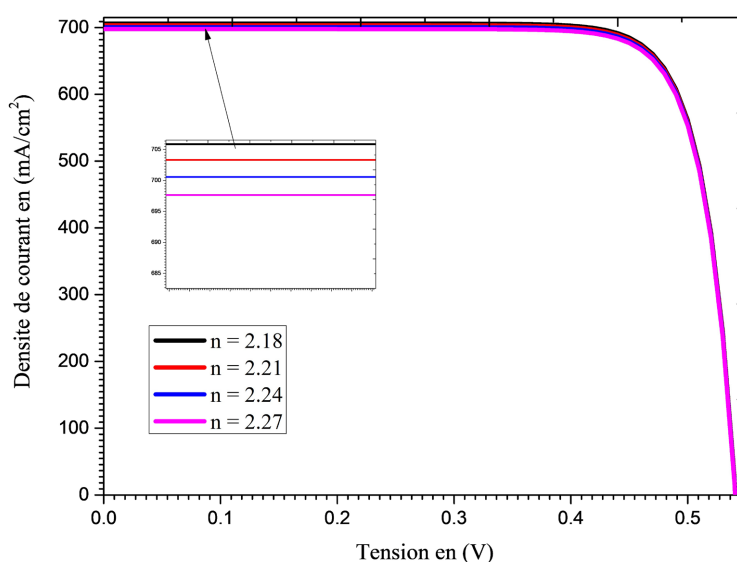


Figure 4. I-V characteristic of a cell coated with a monolayer (ZrO_2) for different refractive indices.

3.4. Effect of the Thickness of the Anti-Reflective Coating (ZrO_2) on the I-V Characteristic

For a given refractive index ($n = 2.18$, at the reference wavelength of 800 nm), the thickness of the anti-reflective coating was varied. The results are shown in Figure 5. It can be seen that for a thickness $e = 91.7 \text{ nm}$, the short-circuit current density is of the order of 705.7 mA/cm^2 , whereas for a thickness $e = 165.1 \text{ nm}$ it is of the

order of 495.5 mA/cm^2 . This shows that as the thickness of the anti-reflective layer increases beyond the quarter-wave value, the short-circuit current density decreases.

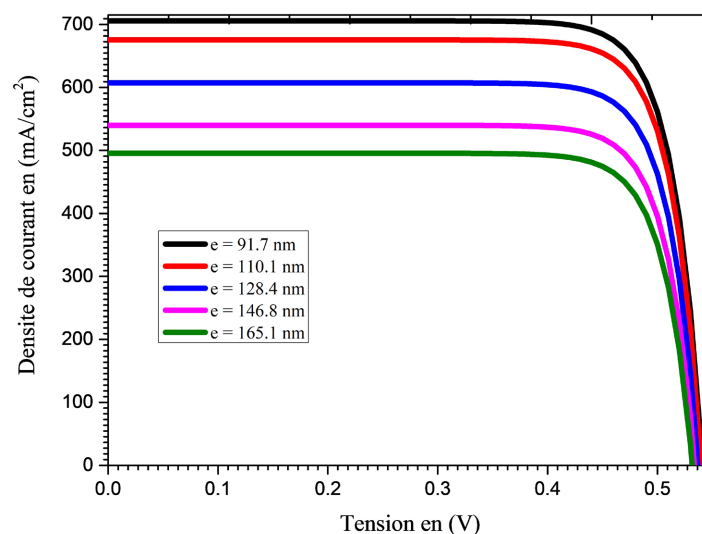


Figure 5. I-V characteristic of a cell coated with a monolayer (ZrO_2) for different thicknesses.

This behaviour is an interference effect. The coating is transparent between 400 and 800 nm ($k = 0$ in the model), so that a thicker layer neither absorbs nor delays the photons; what changes is the phase difference $\varphi = 4\pi n_2 e / \lambda$ between the waves reflected at the air/coating and coating/silicon interfaces (Equation (5)). For $e = 91.7 \text{ nm}$, the layer is a quarter-wave layer at the reference wavelength ($n_2 e = \lambda/4$ at 800 nm, $\varphi = \pi$): the two reflected waves interfere destructively and the reflectance is minimal. As e moves away from this value, the quarter-wave condition is progressively lost (thickness detuning), the reflectance minimum shifts away from the design wavelength and the reflectance integrated over the spectrum increases, so that fewer photons are transmitted into the silicon. For $e = 165.1 \text{ nm}$, the optical thickness $n_2 e \approx 360 \text{ nm}$ corresponds to a half-wave layer for $\lambda \approx 720 \text{ nm}$ ($\varphi = 2\pi$): the reflected waves are then in phase and the reflectance at that wavelength equals that of bare silicon. This explains why the short-circuit current density obtained for this thickness (495.5 mA/cm^2) comes close to that of the uncoated cell (480 mA/cm^2). A strong sensitivity of the short-circuit current to layer thickness has also been reported in simulation studies of other thin-film solar cell architectures [26].

3.5. Power

3.5.1. Power Output of a Bare Monocrystalline Silicon Solar Cell

Figure 6 shows how power varies with voltage. It can be seen that the power varies linearly until it reaches its maximum value (198.89 mW/cm^2) at 0.45 V . It then decreases rapidly, reaching 0 mW/cm^2 at 0.52 V .

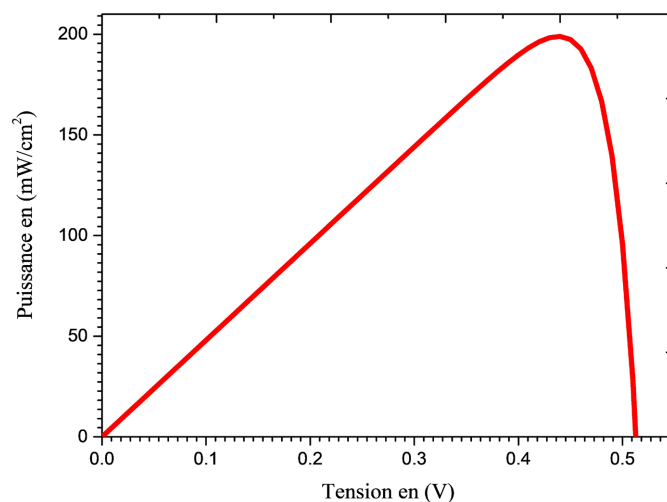


Figure 6. Power output of a bare silicon solar cell.

3.5.2. Power Output of a Solar Cell Coated with Different Anti-Reflective Monolayers

Figure 7 shows the variation in power output of a solar cell coated with different anti-reflective monolayers as a function of voltage. It can be seen that the power output of the cell coated with ZrO_2 increases linearly until it reaches its maximum value (298.78 mW/cm^2) at 0.44 V . It then decreases rapidly, reaching 0 mW/cm^2 at 0.52 V . Meanwhile, the cell coated with MgF_2 reached its maximum power (270.08 mW/cm^2) at 0.44 V . It then decreases rapidly, reaching 0 mW/cm^2 at 0.52 V . It can be seen that the cell coated with ZrO_2 has a higher power output than the other cells. This can be explained by the fact that the current density of the cell coated with ZrO_2 is higher than that of the other cells.

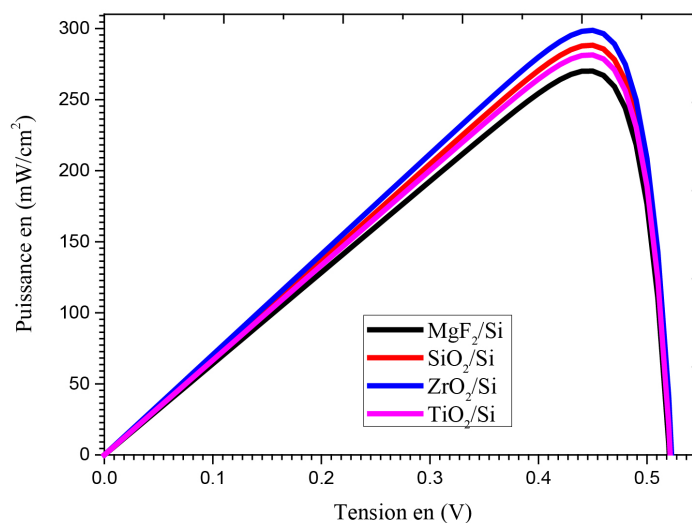


Figure 7. Power output of a solar cell coated with an anti-reflective monolayer.

It is also observed that the power output of the cell coated with the anti-reflec-

tive monolayer is improved by approximately 50.22 per cent compared with the uncoated cell, the relative gain being calculated with respect to the bare-silicon reference, $(298.78 - 198.89)/198.89$. This substantial improvement in power output, linked to the reduction in optical reflection, is consistent with the efficiency gains reported in the literature for solar cells coated with SiO₂ and TiO₂-based anti-reflective layers [27] [4].

4. Conclusions

Building on the reduction in reflectance and the gain in external quantum efficiency established for four anti-reflective coatings (MgF₂, SiO₂, ZrO₂ and TiO₂) in a companion study, this work examined how these coatings translate into electrical gains for a silicon solar cell. The current-voltage characteristics show that the ZrO₂-coated cell reaches the highest short-circuit current density, roughly 47 per cent above that of bare silicon, while its maximum power output rises from 198.89 mW/cm² to 298.78 mW/cm², a gain of about 50.22 per cent. Taken together, the optical and electrical results point to the same conclusion: coating silicon solar cells with an anti-reflective layer, ZrO₂ in particular, is a simple and efficient route to markedly better opto-electrical performance.

It should be noted that this study does not take into account the effect of temperature on the electrical performance of the cell, although it is well established that temperature causes a significant reduction in the power output of crystalline silicon solar cells [28]; the integration of passive cooling solutions, such as the nanofluid layers studied for photovoltaic modules [29], could therefore represent an interesting avenue for further research to complement this study.

Author Contributions

Conceptualization, M.D. and B.B.; methodology, M.D. and A.S.; software, M.D. and I.B.; validation, A.B.C., O.A.N., and B.B.; formal analysis, M.D.; investigation, M.D. and I.B.; resources, B.B.; data curation, M.D. and I.B.; writing—original draft preparation, M.D.; writing—review and editing, A.S., A.B.C., and O.A.N.; visualization, M.D. and I.B.; supervision, B.B.; project administration, B.B. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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