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Improvements in anti-reflection coatings for high-efficiency silicon solar cells

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Abstract

This paper summarizes a theoretical and experimental optimization of several anti-reflection structures for crystalline silicon solar cells. Cases using SiO_2, a Ta_2O_5 single layer and a MgF_2–ZnS double layer over polished surfaces are compared. The optimization was performed using reflection curves and short-circuit current densities obtained from each of the analyzed structures. The optimization procedure was performed as follows: (1) optimizing the thickness and reflection curve of the theoretical structure and (2) obtaining the reflectivity of the closest experimental anti-reflection coating. A very low experimental reflection was observed for the double layer. An experimental short-circuit current density of 37.03 mA cm^{-2} was obtained for the MgF_2–ZnS double layer, while for Ta_2O_5 and SiO_2 single layers the results were 34.84 and 33.00 mA cm^{-2}, respectively. These results were compared with a maximum short circuit current density of 38.70 mA cm^{-2}, for a standard solar cell with no reflection. The reflection curves and short circuit current densities of the double layer are less sensitive to variations in thickness as compared to those of the single layers. © 1998 Elsevier Science S.A.

Keywords: Anti-reflection coating; Optimization layers; Solar cells

1. Introduction

In attempts to decrease reflections in high-efficiency solar cells, several different structures have been used, from SiO_2 single layers to complex structures such as double-layer over inverted pyramid textured surfaces [1,2]. In order to verify the anti-reflection behaviour of high-efficiency silicon solar cells, a theoretical–experimental optimization of several structures including SiO_2 and Ta_2O_5 single layers and a MgF_2–ZnS double layer over polished surfaces has been performed. The theoretical calculations were performed using classical optics theory [3,4]. The experimental Ta_2O_5 and MgF_2–ZnS layers were deposited by vacuum evaporation, while the SiO_2 layer was obtained in a high-temperature open tube furnace. The thicknesses of the experimental layers were measured by ellipsometry and the hemispherical reflections by spectrophotometry. Actually, all high-efficiency silicon solar cells use a thin passivating silicon dioxide layer under the anti-reflection coating. Surface passivation allows the otpimization of solar cells with moderately doped and relatively deep emitters, which produce a low recombination current and a maximum quantum collection efficiency [5–9].

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2. Theoretical–experimental comparison

Initially, a theoretical optimization of single SiO_2 and Ta_2O_5 and double MgF_2–ZnS antireflection coatings was performed with a 5 nm passivating silicon dioxide layer under the last two structures. However, in order to simplify the experimental research, the theoretical comparison was made without considering this passivating silicon dioxide layer. As will be shown later, the influence of a passivating silicon dioxide layer under the optimized layer thickness is not very important, and the complete structure (with SiO_2) can be easily implemented in the fabrication of the complete solar cell. The optimization criterion is the minimum reflection of the wavelength corresponding to the maximum photon flux of the solar spectrum, taking into account the effectiveness of carrier collection through the internal quantum efficiency. To simplify the theoretical calculations, the refractive index of silicon was assumed to be dependent on the wavelength, while for dielectric coatings the index was constant. The simplification was extended by considering the imaginary parts of the refractive indices of silicon and the coating materials to be zero, and assuming both to be weakly absorbing materials [10]. Thus, to compare the quality of different anti-reflection coatings in the best manner, short-circuit current density calculations have been used, considering a solar spectrum AM 1.5 G photon flux [11] and the internal quantum efficiency of a standard cell.

The short-circuit current density is given by:

$$J=q\int_{\lambda_1}^{\lambda_2} F(\lambda)[1-R(\lambda)]Q_i(\lambda)\,d\lambda \qquad (1)$$

where q is the electronic charge, λ_1 and λ_2 are the wavelength limits (350–1100 nm) and $F(\lambda)$ is the photon flux of the solar spectrum, normalized to 100 mW cm^{-2}). The reflections $R(\lambda)$ were calculated theoretically and measured by spectrophotometry for each anaylzed structure. The internal quantum efficiency $Q_i(\lambda)$ (measured at Sandia Laboratories) corresponds to an optimized emitter silicon solar cell (base resistivity $\rho=21\ \Omega\cdot cm$, back aluminium BSF) without any light-trapping improvement [12]. The internal quantum efficiency used can be seen in Fig. 1, and it is possible to observe an excellent short-wavelength behavior produced by emitter optimization. In the cases analyzed in this work, no grid-metal coverage was considered.

SiO_2 was grown by an open tube furnace at a high temperature ($T=1000°C$) for 200 min. The Ta_2O_5 and MgF_2-ZnS layers were deposited by an electron beam, with the thickness being controlled by a quartz crystal. The conditions of Ta_2O_5 layer depositon were as follows: rate 1–2 Å s^{-1}; partial pressure of oxygen $2–5\times10^{-5}$ mbar and a substrate temperature of 150°C. In the case of the double layer, the ZnS deposition rate was 2–3 Å s^{-1} and the substrate temperature was 125°C. MgF_2 was deposited at a rate of 3–5 Å s^{-1} at a substrate temperature of 200°C.

3. Results and discussion

Figs. 2 and 3 show the theoretical optimized reflection as a function of the wavelength, where a comparison between a complete anti-reflection structure (with 5 nm SiO_2) and an unpassivated surface is made. The optimum thickness and short-circuit current density results for the Ta_2O_5 anti-reflection coating are 65.0 nm Ta_2O_5, 5 nm SiO_2 and $J=35.40$ mA cm^{-2} for structures with passivating silicon dioxide, and 71.0 nm Ta_2O_5, 0 nm SiO_2 and $J=35.36$ mA cm^{-2} for structures without passivating silicon dioxide. For double-layer MgF_2-ZnS, the optimum thickness and short-circuit current density results are 108.0 nm MgF_2, 54.0 nm ZnS, 5 nm SiO_2, and $J=37.64$ mA cm^{-2}, and 107.0 nm MgF_2, 60.5 nm ZnS, 0 nm SiO_2 and $J=37.64$ mA cm^{-2} with and without passivating silicon dioxide, respectively. These results show that a 5 nm layer of SiO_2 has a negligible effect on the calculated currents, Therefore, they will be ignored in order to simplify the experimental developments. As can be seen, the experimental tolerances in the acceptable thickness of Ta_2O_5 and ZnS–MgF_2 structures for a good anti-reflection quality indicate that a complete structure can be implemented easily in the fabrication of a complete solar cell. The theoretical optimization assumes refractive indices of $n=1.48$ for SiO_2, $n=2.1$ for Ta_2P_5, $n=1.38$ for MgF_2 and $n=2.33$ for ZnS, according to measurements for our anti-reflection coatings.

The experimental optimization procedure was as fol-

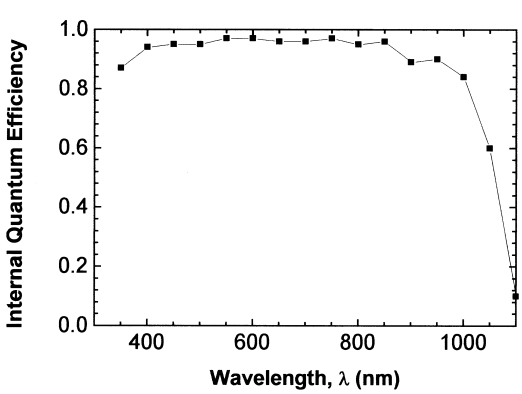

Fig. 1. Internal quantum efficiency as a function of wavelength, according to Ref. [12].

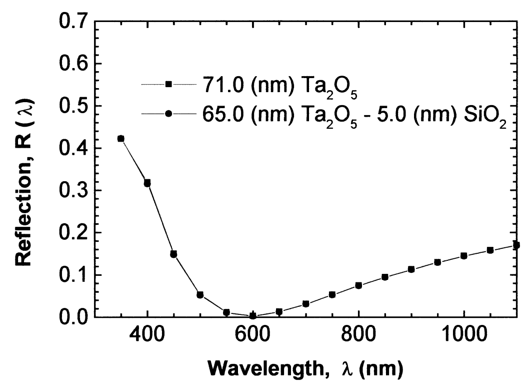

Fig. 2. A comparison between theoretical Ta_2O_5 reflection curves on polished surfaces with and without passivating silicon dioxide using optimized thicknesses.

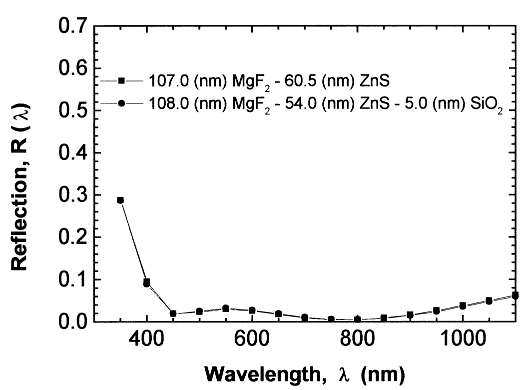

Fig. 3. A comparison between theoretical double-layer reflection curves on polished surfaces with and without passivating silicon dioxide using optimized thicknesses.

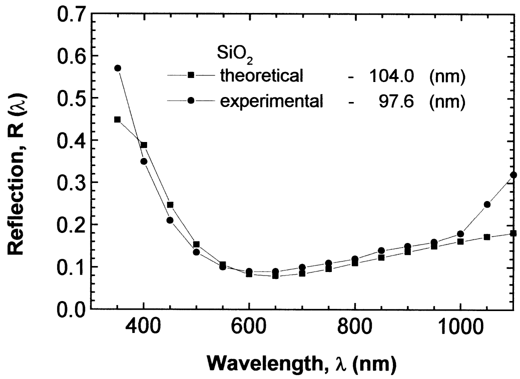

Fig. 4. Theoretical and experimental reflection as a function of wavelength (single-layer SiO_2 on a polished surface).

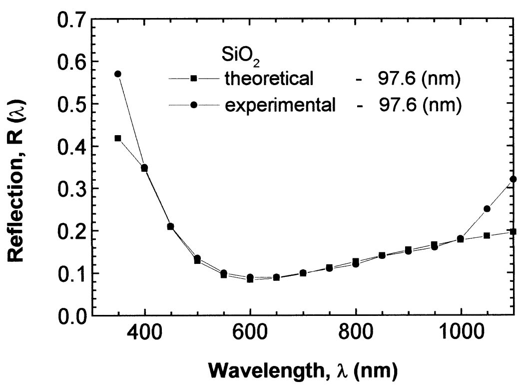

Fig. 5. Comparison of theoretical and experimental reflections versus wavelength (97.6 nm single-layer SiO_2 on a polished surface).

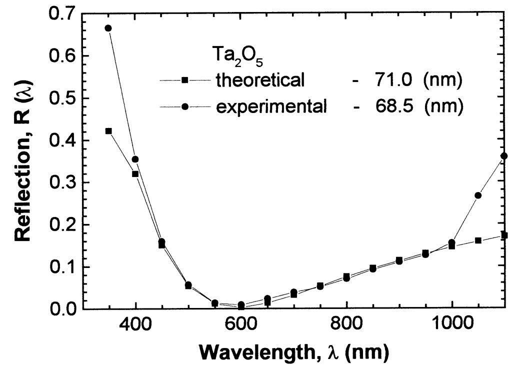

Fig. 6. Theoretical and experimental reflection versus wavelength (single layer Ta_2O_5 on a polished surafce).

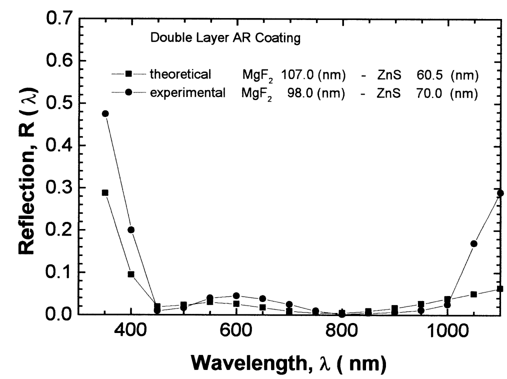

Fig. 7. Theoretical and experimental reflection as a function of wavelength (double layer of MgF_2–ZnS on a polished surface).

lows: once the optimum thickness of the theoretical layers was obtained, the next step was to obtain these thicknesses experimentally. Thus, in the figures which are presented above, the closest experimental results to the theoretical optimization are shown, except for Fig. 5, where the theoretical reflection was calculated to match the experimental curve (SiO_2 single layer with a thickness of 97.6 nm).

The results for theoretical and experimental reflections are given in Figs. 4, 6 and 7 as functions of wavelength, for single and double layers, respectively. Fig. 4 shows a SiO_2 single layer with a thickness of 104.0 nm for the thereotical case and a thickness of 97.6 nm for the experimental case. A slight difference between the theoretical curve (optimum thickness) and the experimental curve (the closest thickness to theoretical results) can be observed. The low reflection reached for the theoretical case ($\lambda < 400$ nm) is due to fact that the simplification used assumes the imaginary parts of the refractive indices of silicon and the coating material to be zero. The increase in reflection at long wavelengths on the experimental curves is caused by light reflections from the rear surface, as verified by measurements of specular and hemispherical reflections. However, this effect was not considered in the calculations. The estimated error in J due to both simplifications can be neglected, since the value assumed by the photon flux of the solar spectrum in these regions (very short and very long wavelengths) is low. Table 1 summarizes the results in terms of the short-circuit current density J. As a reference, the maximum J was obtained assuming total absorption. The theoretical and experimental short-circuit current densities related to the reflection curves are given in Table 1, each being associated with a layer thickness. The losses introduced by each anti-reflection structure are also represented and calculated by means of the relationship between the theoretical or experimental J and the maximum J (reference).

Thus, the short-circuit current density for the case of the SiO_2 single layer, calculated for theoretical (104.0 nm thickness) and experimental (97.6 nm thickness) reflection curves are 33.22 and 33.00 mA cm^{-2}, respectively, while the losses, as regards maximum J, are 14.2 and 14.7%, respectively.

Fig. 5 shows a comparison between the experimental reflection curve and theoretical calculations for a SiO_2 single layer with the same thickness (97.6 nm). Based on this figure, it can be concluded that the simplification (made in theoretical calculations, considering silicon and the coating material to be weakly absorbing), can be applied, at least for wavelengths of $\lambda \geq 400$ nm. The

Table 1
Theoretical–experimetnal single and double anti-reflection layer coating results. Maximum J (0% loss) assumes total absorption. Also, shown are the theoretical and experimental values of J associated with layer thicknesses and the losses produced when compared with the maximum current obtained for each structure

Type of layer	J (0% loss, mA cm^{-2})	Theoretical optimization: W (nm), J (mA cm^{-2})	Experimental results: W (nm), J (mA cm^{-2})	Theoretical Δ_r (%) loss with layers	Experimental Δ_r (%) loss with layers
SiO_2	38.70	104.0, 33.22	97.6, 33.00	14.2	14.7
Ta_2O_5	38.70	71.0, 35.36	68.5, 34.84	8.6	10.0
MgF_2–ZnS	38.70	107.0–60.5, 37.64	98.0–70.0, 37.03	2.7	4.3

low reflection values observed for wavelengths of $\lambda > 1000$ nm are due to no inclusion of light reflection from the rear surface in the theoretical calculations.

Results for the Ta_2O_5 single layer are shown in Fig. 6. The calculated curve represents a layer of 71.0 nm thickness and the obtained experimental curve corresponds to a layer thickness of 68.5 nm. In this figure, a good agreement between both curves can be observed. The behavior for very short and very long wavelengths is caused by same effects as considered above. The short-circuit current densities calculated for the Ta_2O_5 case are 35.36 and 34.84 mA cm^{-2}, with the associated losses being 8.6 and 10.0%, respectively, for the theoretical and experimental cases.

Fig. 7 shows the results for the MgF_2–ZnS double layer. A good agreement between the theoretical curve (107.0 and 60.5 nm, optimum thicknesses) and the experimental curve (98.0 and 70.0 nm, closest thicknesses) can also be observed, except for very short and very long wavelengths. As mentioned above, for this structure the experimental layer thicknesses were not very close to the theoretical values. However, as the double-layer structure has two minimum reflections, low values of reflections for an extensive range of wavelengths are observed.

Therefore, the reflectivity in double-layer anti-reflection coatings has a rather reduced sensitivity to thickness variations, which is in agreement with the results of other authors [10,13]. The short-circuit current densities calculated for the double layer are 37.64 and 37.03 mA cm^{-2}, respectively, with losses of 2.7 and 4.3 %, respectively, for the losses theoretical and experimental cases.

4. Conclusions

An optimization of coating materials was performed by analyzing the maximum short-circuit current density of several structures and their respective thicknesses. Theoretical predictions were used to carry out the experimental developments. The results obtained were excellent, mainly for the double-layer anti-reflection structure. It was possible to verify that the reflection curves and short-circuit current densities of the double-layer structures are less sensitive to thickness variations as compared to single-layer structures. This behavior allows us to obtain low values of reflectivity over a wide range of wavelengths, although the experimental layer thickness is not close to the theoretical optimized layer thickness. Future work will consist of optimization of anti-reflection coatings over textured surfaces.

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References

[1] M.A. Green, Semiconductor Science Technology, vol. 8, Institute of Physics, Bristol, 1993, pp. 1–2.
[2] J. Zhao, A. Wang, S.R. Wenham, M.A. Green, in: D. Flood (Ed.) 24th IEEE Photovoltaic Specialists Conference, IEEE Press, New York, 1994, pp. 1477–1480.
[3] M. Born, E. Wof, Principles of Optics, 5th ed., Pergamon, New York, 1975.
[4] A. Nussbaum, R.A. Phillips, Contemporary Optics for Scientists and Engineers, Prentice-Hall, Englewood Cliffs, NJ, 1974.
[5] A. Cuevas, M.A. Balbuena, R. Galloni, in: C.R. Baraona (Ed.), 19th IEEE Photovoltaic Specialists Conference, IEEE Press, New York, 1987, pp. 918–924.
[6] A. Cuevas, M.A. Balbuena, in: D. Flood (Ed.), 20th IEEE Photovoltaic Specialists Conference, Ed. by D. Flood, IEEE Press, New York, 1988, pp. 429–434.
[7] A.W. Blakers, J. Zhao, A. Wang, A.M. Milne, X. Dai, M.A. Green, in: W. Palz, G.T. Wrixon, P. Helm (Eds.), 9th European Communities Photovoltaic Solar Energy Conference, Kluwer, Dordrecht, 1989, pp. 328–329.
[8] M.A. Green, High Efficiency Silicon Solar Cells, TransTech, Zurich, 1987, ch. 8, pp. 139–168.
[9] M.A. Green, A.W. Blakers, J. Zhao, A.M. Milne, A. Wang, X. Dai, IEEE Trans. Electron Dev. 37 (2) (1990) 331–336.
[10] J. Zhao, M.A. Green, IEEE Trans. Electron Dev. 38 (8) (1991) 1925–1934.
[11] Richard J. Matson, Keith A. Emergy, Richard E. Bird, Solar Cells, vol. 11, Elsevier, Amsterdam, 1984, pp. 105–145.
[12] A. Cuevas, M.A. Balbuena, in: I. Solomon, B. Equer, D. Helm (Eds.), 8th European Communities Photovoltaic Solar Energy Conference, Kluwer, Dordrecht, 1988, pp. 1186–1191.
[13] G.E. Hellison, R.F. Wood, Solar Cells, vol. 18, Elsevier, Amsterdam, 1996, pp. 93–114.