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Efficiency Enhancement of Si Solar Cells by Using Nanostructured Single and Double Layer Anti-Reflective Coatings

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Abstract

The effect of single and double-layer anti-reflective coatings on efficiency enhancement of silicon solar cells was investigated. The reflectance of different anti-reflection structures were calculated using the transfer matrix method and then to predict the performance of solar cells coated by these structures, the weighted average reflectance curves were used as an input of a PC1D simulation. In contrast to the single-layer anti-reflection coating that has not significant contribution to efficiency enhancement, the double-layer was obtained to be practical to improve the efficiency of Si solar cells. Considerable enhancement in the conversion efficiency (E_{ff}) and short-circuit current density (J_{sc}) were obtained for TiO_2/ SiO_2 double-layer anti-reflective coating.

1. Introduction

Solar cells are a promising approach for terrestrial and space photovoltaic devices and offer a large variety of choices for design and fabrication. A main challenge in improvement of the performance of solar cells is the reflection losses, i.e. an ideal solar cell should absorb all useful photons to generate electrical charge. The more photons absorbed, the more efficiency obtains. Different methods have been used to reduce the reflectance of solar cells. Light trapping and anti-reflection coating (ARC) are amongst the widely applied methods to increase the solar cells efficiency [1-7]. Since the reflection from single-crystalline Si solar cells is more 30%, therefore using ARC layer has been a significant part in designing a high efficient Si solar cell [8-11]. In this case, using of different single-layer and double-layer combinations ARCs of materials such as titanium oxide (TiO_x), silicon oxide (SiO_x), silicon nitride (Si_xN_y) and their combinations with different refractive indices have been reported [12-14]. These coatings produce light resonant structures and work effectively at a specific wavelength interval. Such ARC layers, e.g. TiO_2 and SiO_2 have high chemical resistance and light transparency in the visible and near-IR range [11].

In this work, single and double-layer anti-reflection coatings (SLARCs and DLARCs) were used on top of the bare silicon and the reflectance of Si layer with and without ARCs for different wavelength of sunlight spectrum were compared. The reflectance spectra were used as the input of PC1D to determine their effect on I_{SC}, V, FF and η for a solar cell.

In this study TiO_2, SiO_2, ZnO, and Si_3N_4 layers and binary combinations of them were used to investigate their effects on enhancement of solar cells efficiency. The reflectance of multilayer structures were calculated using the transfer matrix method (TMM) [15] of which details were described elsewhere [16].

2. Structure and Simulation

Fig. 1 shows a schematic representation of DLARCs (AR1 and AR2) on the Si Solar cell. For the SLARC merely one of AR coatings was used.

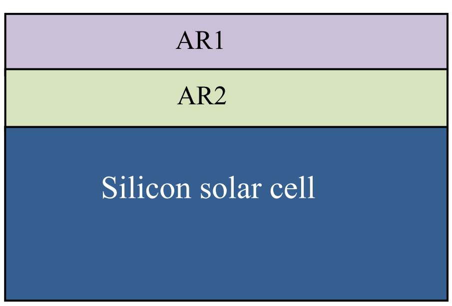

Fig. 1. Schematic view of DLARCs (AR1 and AR2) on the Si Solar cell.

A computational code was produced to calculate the reflectance of multilayer structures. Instead of considering the reflective properties of a specific wavelength, an effective reflectance was computed for these structures over a whole range of the wavelength of incident sunlight. The calculations were carried out with the wavelength-dependent complex refractive indices of materials, that have been tabulated in CRC Handbook of Chemistry and Physics [17].

The solar cell power conversion efficiency relate to the incident light power, P_{in}, as follows:

$$\eta = \frac{P_m}{P_{in}} = \frac{V_{OC}\, I_{SC}\, FF}{P_{in}}$$

Where P_m, I_{SC}, and V_{OC} are the maximum output power, short circuit current and open circuit voltage, respectively. *FF* is the fill factor of the cell that is a symbol of squareness of the current – voltage (I –V) curve and can be calculated by: $FF = \frac{V_m I_m}{V_{OC} I_{SC}}$; with V_m and I_m as the maximum voltage and current.

The simulations were accomplished under AM1.5 sun irradiation for solar cell application. A p-type Si with a thickness of 250 µm was set in the simulation stage with resistively of 1.47 Ωcm and a diffused emitter with error function distribution, where the emitter sheet resistance was 223.5 Ω/sq at 300 K. The base contact resistance was 0.015 Ω and the cell's internal shunt conductance was 0.3 Siemens. The bulk life time of Si was set to 7.03 µs, where the front and back surface recombination velocity was 1800 and 25 cm/s, respectively. The total area of the cell was 100 cm^2.

3. Results and Discussion

Fig. 2 shows the calculated reflectance as a function of wavelength for bare silicon and coated with different ARC layers of TiO_2, SiO_2,

Si_3N_4 and ZnO and the quarter-wavelength thicknesses of 65, 125, 91 and 96 nm were obtained respectively for the above ARC layers. It is known that the thickness of an ARC should be an odd integer multiple of the quarter-wavelength that corresponds to propagation inside the coating medium for a special frequency. In this work all coatings were designed to hold minimum reflection for the incident wavelength of 730 nm. Spectral irradiance of AM1.5 global spectrum in W/m^2 nm as a function of wavelength is also illustrated in Fig. 2.

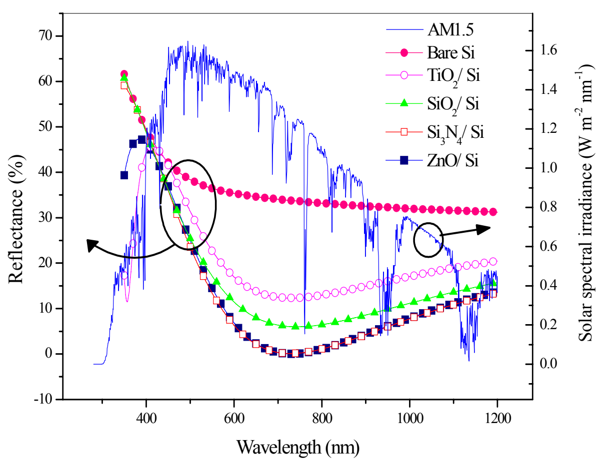

Fig. 2. Reflectance as a function of wavelength for the structures of Si, TiO_2/Si, SiO_2/Si, Si_3N_4/Si, ZnO/Si and also the spectral irradiance of the AM1.5

Fig. 2 demonstrates high reflection (more than 35%) of the bare silicon substrate for visible and near infrared wavelengths. Moreover, ARCs exhibit low reflection <20% for wavelengths longer than 500 nm. Therefore, this figure justifies that adding an anti-reflection layer leads to a decrease of reflectance in 400-1200 nm wavelength range. Among the anti-reflective thin layers, the Si_3N_4 and ZnO have superior performance, such that the reflectance from the layers coated with these ARCs is close to zero for the incident wavelength of 700 nm. Therefore, an anti-reflective structure was designed in this wavelength.

In the next step, the performances of the corresponding cells coated with SLARC which utilized in previous part, are studied. The weighted average reflectance curves are used as an input to PC1D program.

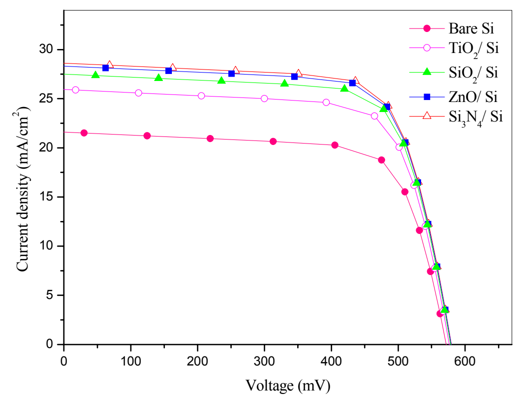

Fig. 3. (I –V) curves of the silicon solar cell without and with TiO_2, SiO_2, Si_3N_4 and ZnO ARC layer.

Fig. 3 shows I–V curves of the silicon solar cell with and without TiO_2, SiO_2, Si_3N_4 and ZnO SLARCs. According to this figure, the ARC structure affects the short circuit current due to the increment of effective photon absorption from the incident light. The ideal materials for the SLARC in Fig. 3 are Si_3N_4 and ZnO. It is obvious that the suitable materials with an optimum refractive index can significantly reduce the reflection of the incident light. On the other hand, the materials employed as ARCs should have other properties such as high energy band gap to reduce the absorption of the incident light too.

The above conditions are of vital importance for SLARCs. In order to further reduce the reflection of Si solar cell in a wider range of wavelengths, DLARCs were considered.

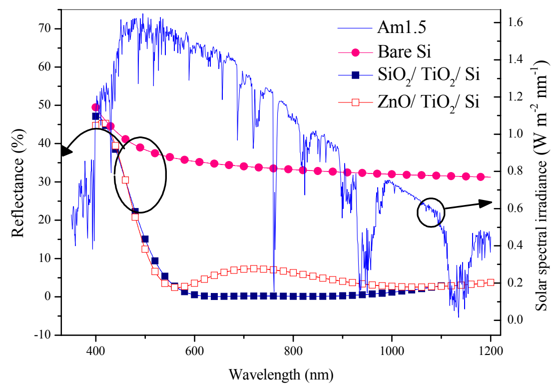

Fig. 4. Calculated reflection characteristics for the AR1 and the AR2 coatings as a function of wavelength and the spectral irradiance of the AM1.5.

Fig. 4 shows the calculated reflectance of a silicon cell with two types of DLARCs consisting of SiO_2 (125 nm)/TiO_2 (65 nm) and ZnO (96 nm)/TiO_2 (65 nm) bilayer. It is observed that DLARCs exhibit lower weighted-average reflectance than that of SLARC. An anti reflective structure in a broad range of wavelength 587-886 nm is observed for TiO_2/SiO_2 DLARC. Taking into account that the large portion of irradiated solar energy is concentrated in this wavelength range, it is expected that a significant improvement to be resulted by using this DLARC.

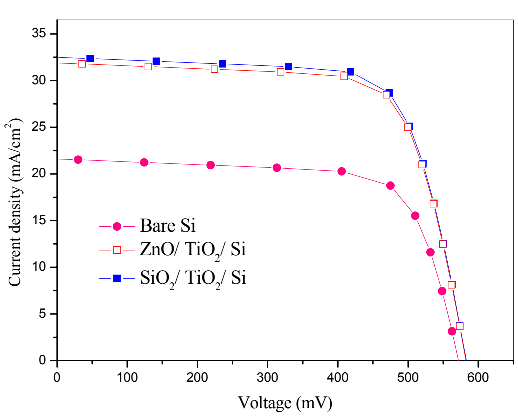

Fig. 5. I-V curves of the solar cell with double- layer ARCs.

Table 1. Photovoltaic data of Si solar cells with SLARC and DLARC under AM1.5 irradiation.

AR Coating	J_{sc} (mA/cm^2)	V_{oc}(V)	FF	η (%)
No ARC	21.60	0.5717	0.722	8.92
TiO_2	25.80	0.5766	0.725	10.78
ZnO	28.31	0.5792	0.718	11.77
Si_3N_4	28.61	0.5795	0.717	11.89
ZnO/TiO_2	31.91	0.5824	0.719	13.37
SiO_2/TiO_2	32.51	0.5829	0.717	13.59

Similar to SLARC, the performances of the cells were evaluated for both cases of DLARCs. The results are depicted in fig. 5. The outcome of simulation shows that employing double layer in solar cells ARC remarkably improves their I-V characteristics.

For a better comparison of photovoltaic parameters obtained at different ARC layers, the results including short-circuit current density J_{sc}, open circuit voltage V_{oc}, fill factor FF, efficiency η are summarized in table 1. Fig. 5 and Table 1 indicate that the short circuit current density is increased by a factor of approximately 47% and 50% using TiO_2/ZnO and TiO_2/SiO_2 AR layers, respectively and a small decrease in FF is not considerable. Any increase in open circuit voltage (V_{oc}) for DLARCs was not observed which can be attributed to their structures. About 3% increase in efficiency can be observed for Si with SLARC compared with bare silicon solar cell. By using TiO_2/SiO_2 DLARC for Si solar cell an efficiency of 13.59% was obtained that corresponds to an increased efficiency of about 52% compared to bare Si. Considering the efficiency of 13.37% for TiO_2/ZnO DLARC, one of these DLARCs can be chosen according to the requirements.

4. Conclusion

The effect of single and double-layer anti reflective coatings were theoretically investigated to reduce the reflectance and improve the efficiency of silicon solar cells. Although the SLARCs were partially acceptable, however DLARCs were designed to obtain more improvements. Results show that an extremely low weighted average reflectance can be achieved using TiO_2/SiO_2 DLARC layers with an increased J_{SC} from 21.60 to 32.51 mA/cm^2 along with photovoltaic efficiency of about 13.59%.

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