Antireflection coatings for GaAs solar cell applications

Z I Alexieva, Z S Nenova, V S Bakardjieva, M M Milanova and Hr M Dikov

1 Central Laboratory of Solar Energy and New Energy Sources, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria
2 Central Laboratory of Applied Physics, Bulgarian Academy of Sciences, 59 St Petersrburg Blvd, 4000 Plovdiv, Bulgaria
E-mail: alexieva@phys.bas.bg

Abstract A double-layer structure of Al₂O₃ over ZrO₂ film is studied. Minimization of the average weighted reflectance is carried out to optimize the thickness of the two layers in the antireflection coating. An optimal value of 2.17% for the weighted average reflection is estimated. The optimal thicknesses of the layers are 49 nm for the bottom and 45 nm for the top layer. Low temperature spin coating technique is used to deposit ZrO₂ and Al₂O₃ films from sol gel solutions on polished silicon wafers, GaAs multilayer heterostructures and AlGaAs/GaAs solar cells. The density of the short-circuit photocurrent increases from 25 mA.cm⁻² for solar cells without an antireflection coating to 36 mA.cm⁻² for those with a double layer coating.

1. Introduction Fabrication of high efficiency solar cells (SC) requires a reduction of the incident light radiation loss through decreasing the solar cell surface reflection. For this purpose, different types of transparent thin film coatings are deposited on the solar cell with appropriate refractive indices and thicknesses – antireflection coatings (ARC). As a result, the reflection losses are minimized, the number of incident photons actually reaching the active areas of the SC is maximized, and the short-circuit current is increased (Jₛ). Unlike many other optoelectronic devices, solar cells operate in a broad range of wavelengths, which means that they need a broadband ARC. The choice of a suitable layer for ARC is very important for the production of high efficiency solar cells. However, it has been demonstrated that single layer coatings are not sufficiently effective - they lead to reflectivity reduction in a narrow spectral range only [1]. A further reflectivity decrease could be achieved using a double-layer ARC with high and low refractive indices respectively. In addition, the optical performance of these coatings is less sensitive to variations in the layer thickness [2]. A widely used double layer ARC for heteroface AlGaAs/GaAs solar cells is the MgF₂/ZnS structure with refractive indices 1.38 and 2.32 respectively and a transmission range 400 –1400 nm. Suitable materials with high refractive indices (2 - 2.4) are also ZrO₂, HfO₂, TiO₂. These layers are stable and durable and are used in combination with low refractive index layers, such as SiO₂ or Al₂O₃. Materials with higher refractive index are preferred for the bottom layer of the ARC and materials with lower refractive index, for the upper layer [3].

3 To whom any correspondence should be addressed.
In this study we consider an alternative set of coatings with Al₂O₃/ZrO₂ films transparent in the range 400 – 900 nm [4]. The layers are deposited from sol solutions by the spin coating – an inexpensive technique with fairly reproducible results.

Optimization was carried out with respect to the thicknesses of the two layers in a double-layer Al₂O₃/ZrO₂ ARC on a GaAs substrate covered with a thin Al₀.₈Ga₀.₂As window layer. Subsequently, layers with optimal thicknesses were deposited on AlGaAs/GaAs solar cells. A relatively good agreement was obtained between the calculated and the experimental reflection data. The short-circuit current of the solar cells with the optimized ARC increased as compared to that of cells without ARC.

2. Experimental

2.1. Solar cell fabrication

The solar cell was fabricated on an A⁺B² multilayer heterostructure grown by liquid phase epitaxy. It consisted of a low resistivity n⁺-GaAs:Si(100) substrate; an n-AlGaAs buffer layer (back surface field - BSF); an n - GaAs: Te base; a p - GaAs: Mg emitter; a p-AlGaAs: Mg window; a p⁺ - GaAs: Mg contact layer; front and back Sn/Ni/Al multi-metal contacts; an antireflection coating Al₂O₃/ZrO₂. Figure 1 presents a cross-section of a AlGaAs/GaAs heteroface solar cell with a cap layer for contact formation.

The characteristics of the solar cell were evaluated before and after ARC deposition. The external quantum efficiency (EQE), the reflection from the surface of the solar cell, the short-circuit current (J_sc), and the open circuit voltage (V_oc) were measured. The EQE measurements were carried out in the spectral range of 340 - 920 nm. The photoresponse in absolute units was evaluated by comparing the photocurrent magnitude of a calibrated reference cell (NASA Lewis Research Center) and the structure under test at monochromatic illumination. The J_sc and V_oc were measured under exposure by a halogen lamp with intensity of 100 mW/cm².

2.2. ARC deposition

The layers were deposited from sol solutions by spin coating for 20sec. The spinning rate was varied in the range 6000 - 8000 rpm depending on the solution used. Al₂O₃ was deposited from an aluminum sol (aluminum butilate), followed by low temperature annealing at 400 °C for 15 min in N₂ ambient to removing the organic components [5]. ZrO₂ was deposited from tri-isopropoxide [6]. Substrate heating during the coating process improved the quality of the layers deposited.

Single and double layers of ZrO₂, Al₂O₃ and Al₂O₃/ZrO₂ were deposited on three types of substrates: 1 - polished silicon wafers, 2 - GaAs substrates with a multilayer heterostructure and 3 – solar cells on the basis of these structures. The layers on polished silicon wafers were used to determine the refractive indices using a He-Ne laser ellipsometer at 632.8 nm (LEF-3M, produced by the Russian Academy of Sciences, Novosibirsk). The reflectance of all sample types was measured by a Shimadzu UV-VIS-IR 3600 Spectrophotometer in the range 400 - 900 nm with an attachment for specular reflectance measurement at 5° angle of incidence.

2.3. Calculation of the reflectivity; minimization of the average weighted reflection

We modelled the reflectivity at normal incidence the structure AlₓGa₁₋ₓAs layer on a GaAs substrate with a double-layer of Al₂O₃/ZrO₂. The thickness of the window layer (30 nm) and its aluminium content (0.8) were determined by anodic oxidation and Raman spectroscopy [7]. The complex refractive indices of GaAs and Al₀.₈Ga₀.₂As for the range 400 – 900 nm were taken from Aspnes et al. [8]
and spline interpolated. The transfer matrix method of Abeles [9] was employed to determine the reflectance of the system, as this method can be used for analysis of multi-layer systems with varying thickness, refractive indices (n) and extinction coefficients (k) on a substrate.

Since the reflectivity varies with the wavelength, we used the average weighted reflectance to assess the efficiency of the system modeled [1]:

\[ RW = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} R(\lambda)N_{ph}(\lambda)d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} N_{ph}(\lambda)d\lambda} \],

where \( R(\lambda) \) is the wavelength-dependent reflection and \( N_{ph} \) is the photo flux of the AM1.5 (air mass 1.5) solar spectrum as a function of the wavelength. The data for the AM1.5 spectrum were taken from the site of the American Society for Testing and Materials (ASTM).

Since the refractive indices of ZrO\(_2\) and Al\(_2\)O\(_3\) were determined experimentally and could not be varied, the optimal thickness of the two layers in the double layer ARC was sought by minimizing the weighted average reflectance for two-layer: Al\(_2\)O\(_3\)/ZrO\(_2\)/Al\(_{0.8}\)Ga\(_{0.2}\)As/GaAs. The minimization was carried out using the Simplex search method.

3. Results and discussion

The minimization of the average weighted reflectance for the double layer structure on a 30 nm thick Al\(_{0.8}\)Ga\(_{0.2}\)As window layer on GaAs resulted in 49 nm thickness of the lower (ZrO\(_2\)) layer and 45 nm for the top (Al\(_2\)O\(_3\)) layer. The value of the minimized average weighted reflectance was 2.17%.

Figure 2 shows the modeled reflectance of the structure Al\(_2\)O\(_3\)/ZrO\(_2\)/Al\(_{0.8}\)Ga\(_{0.2}\)As/GaAs for these optimal layer thicknesses. The modeled reflectance of the GaAs substrate with an Al\(_{0.8}\)Ga\(_{0.2}\)As window is also presented. The experimental reflectivity of such a structure is given as well.

The density of the short circuit photocurrent (\( J_{sc} \)) was 25 mA.cm\(^{-2}\) for solar cells without ARC. After the deposition of a double layer antireflective coating Al\(_2\)O\(_3\)/ZrO\(_2\), densities of 36 mA.cm\(^{-2}\) were achieved.

The external quantum efficiencies of solar cells with and without an antireflection coating are presented in figure 3. The reflectivity spectrum of the solar cell without ARC is given as well.

4. Conclusion

A double layer antireflection coating was deposited on the front side a AlGaAs/GaAs solar cell by spin coating – a low cost method with good reproducibility. The optimal thickness of the two layers was determined by minimizing the average weighted reflection. A theoretical value of 2.81% was obtained together with thicknesses of the top (Al\(_2\)O\(_3\)) and the bottom (ZrO\(_2\)) layers of 45 nm and 49 nm, respectively. The density of the short-circuit photocurrent (\( J_{sc} \)) increased from 25 mA.cm\(^{-2}\) for solar cells without ARC to 36 mA.cm\(^{-2}\) for those with a double layer ARC.
Acknowledgments
This work was supported by the National Science Fund at the Ministry of Education and Science of Bulgaria under Grants D 03 369/06 and TN 1504.

References
[1] Richards B S 2003 Solar Energy Materials & Solar Cells 79 369
[2] Sttehlke S, Bastide S, Guillet J and Levy-Clement C 2000 Mat. Sci. Eng. B 69 81
[3] Algora C and Alcaraz M F 1990 IEEE Trans. Electron Devices 44 1499
[4] Vitanov P, Harizanova A, Ivanova T and Dimitrova T 2010 Materials Sci and Engin. IOP Conf. Series 8 012027
[5] Vitanov P, Harizanova A, Ivanova T and Dimitrova T 2009 Thin Solid Films 517 6327
[6] Vitanov P, Tsanev A, Stefanov P, Harizanova A and Ivanova T 2007 J. Optoelect. Adv. Mater. 9 256
[7] Milanova M, Kakanakov R D, Arnaudov B, Evtimova S, Vitanov P, Goranova E, Ivanov P, Alexieva Z, Shivarts M, Timoshina K and Vlasov A 2009 Proc. Workshop Nanosci. & Nanotechnol. ed E Balabanova and I Dragieva (November 2008 Sofia Bulgaria) 8 124
[8] Aspnes D E, Keiso S M, Logan R A and Bhat R 1986 J. Appl. Phys. 60 754
[9] Abeles F 1950 Annals de Physique 5 596