Nanostructured multilayer graded-index antireflection coating for Si solar cells with broadband and omnidirectional characteristics

Sameer Chhajed, Martin F. Schubert, Jong Kyu Kim, and E. Fred Schubert

Citation: Appl. Phys. Lett. 93, 251108 (2008); doi: 10.1063/1.3050463
View online: http://dx.doi.org/10.1063/1.3050463
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v93/i25
Published by the American Institute of Physics.

Related Articles
Fourier transform infrared absorption spectroscopy characterization of gaseous atmospheric pressure plasmas with 2 mm spatial resolution
Antireflective ZnSnO/Ag bilayer-based transparent source and drain electrodes for transparent thin film transistors
Ultrasonic evaluation of early damage of a coating by using second-harmonic generation technique
Electrochromic switchable mirror glass with controllable reflectance
Modeling of silicon nanocrystals based down-shifter for enhanced silicon solar cell performance

Additional information on Appl. Phys. Lett.
Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors
Nanostructured multilayer graded-index antireflection coating for Si solar cells with broadband and omnidirectional characteristics

Sameer Chhajed,1 Martin F. Schubert,1 Jong Kyu Kim,1 and E. Fred Schubert1,2,a)
1Future Chips Constellation, Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
2Future Chips Constellation, Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180, USA

Design, fabrication, and characterization of a broadband, omnidirectional, graded-index antireflection (AR) coating made using nanostructured low-refractive-index (n=1.05–1.40) silica deposited by oblique-angle deposition are reported. Averaged over wavelength range from 400 to 1100 nm and 0°–90° angle of incidence, polished Si reflects ∼37% of incident radiation. The reflection losses are reduced to only 5.9% by applying a three-layer graded-index AR coating to Si. Our experimental results are in excellent agreement with theoretical calculations. The AR coatings reported here can be optimized for photovoltaic cells made of any type of material. © 2008 American Institute of Physics. [DOI: 10.1063/1.3050463]

Despite the early discovery of the photovoltaic (PV) effect by Becquerel in 1839 and almost 125 years since the first solar cell was built in 1883 by Fritts, PV cells have seen limited commercial success until recently. The primary reason for this is the low efficiency and corresponding high cost per kWh of energy produced by PV cells. Even today, Si solar cells have efficiency at best just over 20% (Ref. 1) and it has not improved much over the past decade.2 Reflection of incident light from the surface of the solar cell is one of the major optical loss mechanisms seriously affecting the solar cell efficiency. Figure 1 shows the broadband nature of solar irradiance spectrum. Nearly 90% of commercial solar cells are made of crystalline Si.3,4 A polished Si surface reflects as much as ∼37% light when averaged over all angles of incidence (0°–90°) and range of wavelengths of the solar spectrum that can be absorbed by Si (400–1100 nm).

For several years, the reduction in reflection from the surface of the solar cell has been one of the primary focuses of solar cell research.3–10 Conventional, a single layer antireflection (AR) coating with an optical thickness equal to one-quarter of the wavelength of interest is used. Ideally such single layer λ/4 AR coating should have refractive index (RI), nλ/4, given by

\[ n_{\lambda/4} = \sqrt{n_{\text{semiconductor}} \times n_{\text{air}}} \]  \tag{1}

Often due to the unavailability of materials desired, exact value of the RI, the performance of such λ/4 AR coatings deviates from the optimum. For example, SiO2, which has a RI value between that of Si and air, is used for Si solar cells. However, fundamentally these single layer AR coatings can minimize reflection only for one specific wavelength and for one specific angle of incidence (AOI), typically for normal incidence. The conventional SiO2 single layer AR coating is inherently unable to cover the broad range of wavelengths present in a solar spectrum and the broad range of AOIs. These coatings reduce the reflection to ∼18%. In order to reduce the reflection further, surface texturing is often used, which has shown to reduce the reflection to ∼13%.12,13

However, unlike any other method, the approach described in this paper offers unique advantages such as tunability of RI of the single material, flexibility in the choice of the material, simplicity of the physical vapor deposition process, and freedom of optimization for any substrate-ambient material system, all at once. As a proof of concept demonstration we report the fabrication of an optimized three-layer AR coating for Si solar cell.

Rayleigh, in 1880, mathematically demonstrated that graded-RI layers have broadband AR properties. However, until recently, due to the unavailability of optical materials with very-low RIs (n < 1.4), such near-perfect graded-index AR coatings could not be realized. We have recently demonstrated a RI as low as 1.05 for SiO2.14,15 Other groups have also reported the theory and application of this technique to produce porous broadband AR coatings.16 It is now possible to tune the RIs of an optical material to virtually any value between its bulk value and 1. Next, a systematic study of multilayer AR coatings is performed. For multilayer AR coatings, the RI of the layers is graded, i.e., gradually decreased, from the semiconductor to air. This can be done either in a continuous fashion or in discrete steps. Since the broadband solar spectrum is incident on the solar cell over a

FIG. 1. (Color online) Solar spectrum and reflectance of Si substrate with (a) no AR, (b) λ/4 AR, and (c) three-layer AR coating.

---

1Electronic mail: efschubert@rpi.edu.

(Received 10 November 2008; accepted 25 November 2008; published online 24 December 2008)
wide range of angles during the course of the day, it is important to use a figure of merit which gives a fair comparison of the performance of various AR coatings. We use $R_{av}$ which is defined as follows:

$$R_{av} = \frac{1}{\Delta \lambda} \frac{1}{\Delta \theta} \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} R d\theta d\lambda,$$

where $\theta$ is the zenith angle.

All coatings are optimized in the wavelength range of 400–1100 nm and AOI range of 0°–90°. The details of the MATLAB optimization algorithm are discussed elsewhere.\textsuperscript{17}

A three-layer AR coating, optimized for polished Si solar cells, is fabricated and characterized, as described in the next section. For simplicity of design and fabrication, only the thickness $t$ of each layer in the three-layer graded index is varied during optimization while keeping the RI $n$ fixed for each. Bulk TiO$_2$ is chosen as material for the first layer due to its high RI value, bulk SiO$_2$ for the second layer, and 80% porous SiO$_2$ for the third layer. This choice is made only for simplicity and is not due to the limitation of any kind. Figure 2 shows the surface plots of calculated reflectance for Si substrate (a) with no AR coating, (b) with a conventional $\lambda/4$ Si$_3$N$_4$ AR coating, and (c) with three-layer graded-index AR coating. The significant advantages of the three-layer graded-index AR coating in terms of drastically reduced reflectance over a wide range of wavelengths and AOIs are elucidated by the plots.

The $\lambda/4$ Si$_3$N$_4$ AR coating in sample (b) is deposited using a reactive rf sputtering and is optimized for lowest normal incidence reflectance at 550 nm wavelength and has a RI, $n=2.2$, measured at 550 nm and thickness, $t=62.5$ nm. The three-layer AR coating in sample (c) is deposited over a polished crystalline Si substrate using rf sputtering for the first two layers and oblique-angle e-beam evaporation for the third layer. The schematic of the AR coating is shown in Fig. 3(a). It is composed of the first layer of TiO$_2$ ($n=2.66$ at 550 nm), the second layer of SiO$_2$ ($n=1.47$ at 550 nm), and the third layer of low-$n$ SiO$_2$ ($n=1.07$ at 550 nm). The thicknesses of each layer are 45, 120, and 200 nm, respectively. The first layer of TiO$_2$ is deposited by reactive sputtering using 200 W of rf power to the 2 in. TiO$_2$ target, 5.0 SCCM (SCCM denotes cubic centimeter per minute at STP) of Ar, and 0.5 SCCM of O$_2$ for 60 min at an operating pressure of 2 mTorr. A substrate bias of 5 W is used without any external heating. The third layer of porous SiO$_2$ is deposited using oblique-angle e-beam evaporation technique. The desired low RI is achieved by mounting the sample such that the substrate normal is at 85° to the incoming flux. Details of the oblique-angle evaporation technique have been discussed elsewhere.\textsuperscript{18–20} The thickness and RI values are measured using ellipsometry. The thickness is confirmed using scanning electron microscopy (SEM). Figure 3(b) shows the SEM image of the three-layer AR coating.

The absolute reflectance of samples (a)–(c) are measured using the variable angle spectroscopic ellipsometry. For each sample, data are measured for wavelengths between 400 and 750 nm and for AOIs between 40° and 80° with 1° increments. This restricted choice of range is due to the limitation of the measurement equipment. However, it serves the purpose of comparison of measured and calculated values in the same range without any loss of accuracy. A large number of data points ensure accuracy in $R_{av}$ obtained from the measurement. Figure 4 shows the surface plots of the measured reflectance data. Figure 4(c), in contrast with Fig. 4(b), shows very-low reflectance over a wide range of wavelengths and AOIs, clearly demonstrating the predicted broadband and omnidirectional characteristics of the three-layer graded-index AR coating.

The measured absolute reflectance results are in excellent agreement with the theoretically calculated values shown in Fig. 2. The resultant $R_{av}$ for samples (a)–(c) are 37.0%, 17.3%, and 5.9%, respectively. Figure 5 shows the photograph of the three samples for side-by-side comparison. The $\lambda/4$ AR coating shows blue color due to its significantly high reflectance in the wavelength range below the zero-reflection wavelength of 550 nm. The superiority of the three-layer AR coating is clearly evident.
In conclusion, we have demonstrated a broadband, omnidirectional, graded-index AR coating. The availability of the nanostructured low-\( n \) materials deposited by oblique-angle deposition technique has allowed the design of near-perfect AR coatings which can be used in a wide variety of applications. Generally porous films are mechanically not as stable as dense films. However, this was not a concern for our research related to optical properties of the thin film coatings. No disintegration, degradation of performance, or other adverse effect was observed even after several months. In specific cases, it may be practical to limit the maximum allowable porosity of the films to achieve desired mechanical properties. Additional means may be employed to protect the top layer, such as a thin pour closure or capping layer. Measurements show dramatic reduction in reflection over a wide range of AOI and a broad range of wavelengths in comparison with conventional \( \lambda / 4 \) AR coatings. The average reflectance, \( R_{\text{av}} \), of 5.9\% was measured for the triple-layer graded-index AR coating as compared to 17.3\% for the conventional Si\(_3\)N\(_4\) \( \lambda / 4 \) AR coating widely used for Si solar cells. These values are in excellent agreement with the theoretical calculations which predict \( R_{\text{av}} \) of 4.9\% for the triple-layer graded-index AR coating and 18.2\% for the \( \lambda / 4 \) AR coating. This broadband and omnidirectional character of our AR coating is very well suited for application in solar cells.

Support by the National Science Foundation (USA), Sandia National Laboratories (USA), Department of Energy (USA), Crystal IS (USA), Samsung Electro-Mechanics Co. (Korea), and Troy Research Corporation (USA) is gratefully acknowledged.