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# Tri-layer antireflection coatings ($SiO_2/SiO_2–TiO_2/TiO_2$) for silicon solar cells using a sol–gel technique

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**Abstract**

Antireflection coatings (ARCs) have become one of the key issues for mass production of Si solar cells. They are generally performed by vacuum processes such as thermal evaporation, reactive sputtering, and plasma-enhanced chemical vapor deposition. In this work, a sol–gel method has been demonstrated to prepare the ARCs for the non-textured monocrystalline Si solar cells. The spin-coated $TiO_2$ single-layer, $SiO_2/TiO_2$ double-layer and $SiO_2/SiO_2–TiO_2/TiO_2$ triple-layer ARCs were deposited on the Si solar cells and they showed good uniformity in thickness. The measured average optical reflectance (400–1000 nm) was about 9.3, 6.2 and 3.2% for the single-layer, double-layer and triple-layer ARCs, respectively. Good correlation between theoretical and experimental data was obtained. Under a triple-layer ARC condition, a 39% improvement in the efficiency of the monocrystalline Si solar cell was achieved. These indicate that the sol–gel ARC process has high potential for low-cost solar cell fabrication.


*Keywords:* silicon; antireflection coating; sol–gel; $TiO_2$; $SiO_2$; solar cell

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## 1. Introduction

Antireflection coatings (ARCs) are widely used in various applications such as display panels, solar cells and optical lenses [1–3]. Thin-film ARCs can greatly reduce the optical loss in multi-element lenses by making use of phase changes and the dependence of the reflectivity on refraction index. A thin, dielectric film or several such films were applied to an optical surface to reduce its reflectance and thereby increase its transmittance. A single-layer ARC can be non-reflective only at one wavelength, usually at the middle of the visible region. Multiple layers are more effective over the entire visible spectrum. Several transparent and high refractive-index material films have already been applied to ARC techniques, e.g. SiO ($n = 1.8$–$1.9$), $SiO_2$ ($n = 1.44$), $Si_3N_4$ ($n = 1.9$), $TiO_2$ ($n = 2.3$), $Al_2O_3$ ($n = 1.86$), $Ta_2O_5$ ($n = 2.26$), $SiO_2$–$TiO_2$ ($n = 1.8$–$1.96$) and ZnS [4–9]. Optical coatings are generally performed by vacuum processes such as thermal evaporation, reactive sputtering, and plasma-enhanced chemical vapor deposition (PECVD). All these methods are capable of producing films with uniform thickness and good optical properties. However, the conventional vacuum deposition processes are expensive and unsuitable for continuous mass production techniques in low-cost solar cells. Recently, high refractive-index and high-transparency $Si_3N_4$ or $TiO_2$ single layer and $SiO_2/TiO_2$ double-layer have been developed and applied in solar cell ARCs process. These favorite films are prepared by PECVD and this results in reflectance below 10% [10–12].

Recently, ARCs have become one of the key issues for mass production of mono- and multi-crystalline Si solar cells. The sol–gel technique offers a simple and low-cost process to prepare the high-quality thin films [13,14]. In this work, the $TiO_2$ single-layer, $SiO_2/TiO_2$ double-layer and $SiO_2/SiO_2$–$TiO_2/TiO_2$ triple-layer ARCs on monocrystalline Si solar cells were prepared by a sol–gel spin-coating technique. To achieve minimum reflection of a normal incident wave of a single wavelength, the antireflection coating may consist of a single layer, which must possess (a) a refractive index equal to the square root of the refractive indices of the materials bounding the coating, and (b) a thickness equal to one-quarter of the wavelength (i.e., the wavelength within the material of which the coating consists). However, if one wants to achieve minimum reflection of multiple wavelengths, additional layers must be added. Kern and Tracy have observed an increase of 44% in the cell efficiency after spraying $TiO_2$ single-layer ARC [15]. Green et al. have used $MgF_2$/ZnS double-layer ARCs on Si cells with 19.1% efficiency [16]. In this paper, we present the results of calculations and experiments obtained by sol–gel method of single-layer, double-layer and triple-layer ARCs on polished silicon substrates. For an optimum ARCs design, the refractive index and thickness of each layer must be controllable to achieve the best performance along the desired spectrum. Details of the fabrication process and efficiency improvement will be described.

## 2. Experimental details

### 2.1. Sol–gel and spin coating process

The flow chart of the ARC synthesis process was performed using a sol–gel process as shown in Fig. 1. A clear solution is prepared by reacting metal alkoxide with a mixture of critical amount of water and/or acid in an alcohol diluted medium, and the $SiO_2$, $SiO_2$–$TiO_2$ and $TiO_2$ coatings were spin coated on the Si substrate from the above-said