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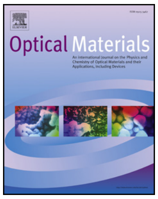

Optimized flexible cover films for improved conversion efficiency in thin film flexible solar cells

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ABSTRACT

Thin film solar cell technologies are being developed for lower cost and flexible applications. For such technologies, it is desirable to have inexpensive, flexible cover strips. In this paper, we demonstrate that transparent silicone cover glass adhesive can be doped with TiO_2 nanoparticles to achieve an optimal refractive index and maximize the performance of the cell. Cells covered with the film doped with nanoparticles at the optimal concentration demonstrated a ~1% increase in photocurrent over the plain (undoped) film. In addition, fused silica beads can be incorporated into the flexible cover slip to realize a built-in pseudomorphic glass diffuser layer as well. This additional degree of freedom in engineering flexible solar cell covers allows maximal performance from a given cell for minimal increased cost.

1. Introduction

The technology of solar cells has progressed rapidly over the years. Conventional polysilicon solar cells, used for commercial and residential application have reached sub-module efficiencies of 21.3%, while multijunction semiconductor solar cells have realized efficiencies of 38.8%. Single crystal silicon has gotten to 26.3% efficiency [1], extremely close to the Schockley-Quiesser limit [2]. The active region of these solar cells has been progressively optimized, and multilayer antireflective coatings are often used for maximum performance [3].

Other technologies are being developed for lower cost and flexible applications, including copper-zinc-tin-sulfide [4] (CZTS), cadmium telluride [5] (CdTe), perovskite-based [6] and silver-indium-selenide cells [7]. These cells trade off ultimate performance for reduced cost.

In general, solar cells need a cover layer to reduce reflection and to protect them from the elements that degrade the device over time. Typically for conventional rigid semiconductor solar cells, the cover layer is glass coated with an antireflection coating. Flexible solar cells, however, require flexible material as a cover layer. Previous research has developed flexible pseudomorphic glass (PMG) to match with space grade solar cells for a complete flexible solution [8,9]. In the space-based experiments, they were tested with high efficiency triple-junction solar cells with power conversion efficiency > 30%.

These flexible PMG films have undergone extensive environmental testing to understand their behavior in the radiation and UV environments of space. In addition, they have been successfully flown in space as test articles aboard the International Space Station as well as in operational satellites [9]. In addition to flexibility, PMG offers the potential for complete encapsulation, thereby reducing electrostatic discharge degradation that has been problematic for geosynchronous satellites. PMG also has a higher thermal emittance than conventional cover glass that allows the solar cells to operate cooler and therefore with higher efficiency.

In this paper, we investigate the use of silicone layers doped with TiO_2 and fused silica beads to alter their optical properties as cover slips for lower cost flexible terrestrial solar cells. This is to our knowledge the first attempt to optimize the effective refractive index of this incoherent, flexible material for improved solar cell performance.

First, the transmissivity through the cover slip into a particular CZTS solar cell is modeled to determine the optimal index for the thick and optically incoherent flexible cover material. Then, polydimethylsiloxane (PDMS) compliant flexible films are fabricated doped with varying concentration of titania (TiO_2) nanoparticles to achieve a variety of effective refractive indices. For each of the various different cover film layers fabricated, the reflectivity and transmissivity were measured directly using a spectrophotometer. Additionally, each of the layers was placed onto a CZTS solar cell and the photocurrent density of a solar Air Mass 1.5 spectrum was also measured. Results showed

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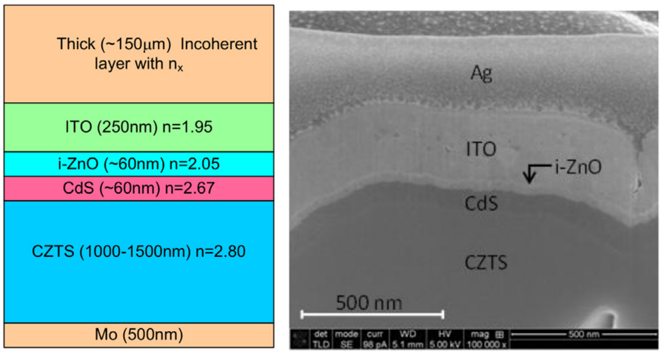


(a) (b)

Fig. 1. (a) composition of CZTS solar cell with AR layer, including glass scattering beads (b) focused-ion-beam cut scanning electron micrograph of CZTS solar cell.

generally good agreement between modeled and measured response and were able to measurably improve cell performance.

2. Experiment

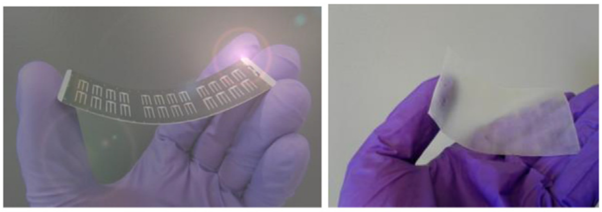
Fig. 1(a) left shows the structure of the CZTS solar cell used as a test case, along with the refractive indices at 500 nm used for the solar cell material and the varying effective index of the top layer. The CZTS cell were fabricated on flexible substrates and had typical power conversion efficiencies of 3–6% [10].

It is well known that a single-layer antireflection coating at a specific wavelength λ can be obtained if the coating layer is λ/4 thick with an index of the geometric average $\sqrt{n_{ambient}\, n_{substrate}}$ of the surrounding indices, in which $n_{ambient}$ is the index of the surrounding (air or vacuum) and $n_{substrate}$ the index of the underlying material. However, in general the thin film solar cell is a complicated stack of various materials of optical thicknesses (~100 nm) and the cover film is much thicker than the coherence length of sunlight (roughly 5 µm). Because it is thicker than the coherence length, interference between top and bottom interfaces cannot cancel reflections and modeling must consider it as an incoherent layer, in which optical intensities (not amplitudes) combine.

There is no simple expression of what the optimal index of the top layer should be in order to minimize the total combined reflectance of the air-coating interface and the coating-cell interface. Increasing the refractive index generally increases the reflectivity at the front surface, but decreases the reflectivity at the glass-solar cell interface, and it is also influenced by the underlying solar cell layers.

The optical model of the solar cell, along with an SEM of the solar cell, is shown in Fig. 1. The top layer (labeled 'incoherent') is the flexible cover slip layer. In order to determine the optimal index, the transmittance and reflectance of sunlight into the stack is modeled using a transfer matrix method [11], with random phase averaging used for the incoherent calculation [12]. Fig. 2 shows a photograph of both the flexible cover film and the flexible solar cell. For testing, the various films were placed on the solar cell and the relative photocurrent (photocurrent of the cell coated with a particular film, divided by total photocurrent of the uncovered cell) was measured.

Fig. 3 shows the calculated reflectance of the stack as a function of the refractive index of the ARC. For this particular solar cell, minimal reflectance occurs at a refractive index of roughly n ≈ 1.7. The experimental target is then to dope PDMS with varying amounts of titania nanoparticles to achieve an effective refractive index close to the simulated optimal value.



(a) (b)

Fig. 2. (a) Photograph of flexible CZTS solar cell (b) photograph of flexible PDMS cover slip doped with fused silica beads.

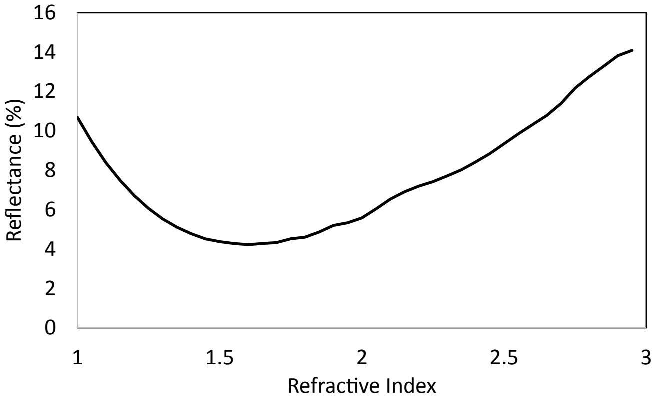


Fig. 3. Reflectance as a function of refractive index of incoherent cover layer for solar cell stack.

3. Methods and materials

The SCV-2590 PDMS was purchased from NuSil Technologies and had a refractive index of approximately 1.45. This is comparable to typical refractive index of rigid solar class cover slips [13]. In addition to the standard ratio of 10:1 silicon elastomer to hydrosiloxane, various amounts of nanoparticles of 22 nm anatase titania (TiO_2) procured from Sigma-Aldrich were added to the mixture. Once the particles are mixed in the proper ratio with the PDMS, they are deposited onto a Kapton sheet mounted on a 6 in. x 6 in. MIC6 Aluminum block, purchased from McMaster-Carr. The Kapton sheet has 150 µm (5 mil) thick Kapton tape guide-rails on either side to ensure the proper thickness of the film. Using a razorblade, the mixture is spread into a film. The apparatus is then inserted into a desiccator for 30 min to release any gases trapped in the film. Once the deaeration is completed, the Kapton sheet is placed into a curing oven for 2 h at 100 °C.

For a potentially more controllable and uniform thickness, the films could be spin-coated rather than doctor-bladed.

TiO_2 has a refractive index of approximately n = 2.70 [14]. Mixing some amount of TiO_2 nanoparticles with the PDMS modifies the transmission and reflection through the film, creating essentially an effective index different than the PDMS alone. The mechanism is both Rayleigh scattering from the small particles and the change in effective index due to the averaging of the index between the values of TiO_2 and of the PDMS. This method is a direct and simple means to create PDMS films with optical properties significantly different than PDMS. Other researchers have fabricated PDMS-TiO_2 hybrid nanocomposites with similar optical properties by chemically combining the two materials [15].

Some films had an additional scattering element in the form of fused silica beads of varying sizes and concentrations incorporated into the film. The purpose is to build in a 'diffusor layer' that will increase the average length of the optical path through the solar cell absorber layers,