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Reflectance Control for Multicrystalline-Silicon Photovoltaic Modules Using Textured-Dielectric Coatings

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ABSTRACT

We describe a new approach for controlling the reflectance of photovoltaic modules with planar-surface solar cells. The new approach uses an optically thick, dielectric coating with a large refractive index and a textured surface; this dielectric coating is deposited on the planar-surface solar cell. The *textured-dielectric coating* works optically with the module encapsulation to promote optical confinement of rays inside the module encapsulation structure, which reduces the net reflectance of the photovoltaic module. The advantage of our approach is that deposition of a textured-dielectric film may be less costly and less intrusive on the cell manufacturing process than texturing multicrystalline-silicon substrates. We present detailed optical models and experimental confirmation of our new approach.

INTRODUCTION

Reflectance control is a major issue for multicrystalline-silicon (mc-Si) photovoltaic modules. Single-crystal silicon (sc-Si) cells commonly use anisotropic etches to form a textured surface to reduce surface reflectance. These anisotropic etches are less effective with mc-Si substrates because the grains have random crystal orientations [1]. We estimate that the active-area solar-weighted reflectances of crystalline-silicon (c-Si) modules are around 15% and 5% for modules with planar and textured c-Si cells with single-layer antireflection (SLAR) coatings, respectively. This difference in reflectance reduces the performance of commercial mc-Si modules with planar SLAR cells about 1.5% absolute compared to commercial sc-Si modules with textured SLAR cells.

Several methods have been investigated to texture mc-Si to reduce reflectance losses. These methods include the following: isotropic chemical etches with masks [2], scribing the surface with a laser [2], mechanically texturing the surface with a dicing wheel or saw [3], and chemically texturing the surface with anodic HF porous-silicon etchants [4]. While these approaches have achieved very low reflectances, none of these approaches have been commercialized due to various economic and technical difficulties.

Solar cells are typically encapsulated in photovoltaic modules for environmental stability. This paper describes a new approach for reflectance control that examines the reflectance of the mc-Si cell *in the encapsulated module.* Rather than texturing the silicon substrate, our approach deposits a dielectric film on the planar mc-Si cell; this dielectric film is optically thick and has a textured surface and a large refractive index (n>2). The *textured-dielectric coating* works optically with the module encapsulation to promote optical confinement of rays inside the module encapsulation, which reduces the net reflectance of the photovoltaic module. The advantage of our approach is that deposition of a textured-dielectric film may be less costly and less intrusive on the cell manufacturing process than texturing mc-Si substrates.

Takato *et alia* recently demonstrated use of textured antireflection coatings for mc-Si solar cells [5]. They demonstrated improvement of current and long-wavelength spectral response compared to a planar SLAR c-Si cell, which they attributed to optical confinement in the textured ZnO coating. These authors, however, did not present a detailed optical model of their films and did not recognize the advantages of textured-dielectric coatings for reflectance control in photovoltaic modules.

We first describe how the textured-dielectric coating works optically in a module. Next, we describe an optical model of photovoltaic modules, and use this model to demonstrate that a textured-dielectric coating can reduce module reflectance almost as much as a textured silicon surface. Finally, we present experimental confirmation of our optical models and of the usefulness of textured-dielectric coatings.

TEXTURED-DIELECTRIC CONCEPT

The textured-dielectric film over the silicon cell randomizes the direction of reflected rays inside the encapsulant (glass) and inside the high-refractive-index dielectric film. (Due to the similar refractive indices for glass and typical encapsulants, the optical interface between the encapsulant and the glass is ignored. "Glass" and "encapsulant" are used interchangeably in this paper.) The random direction of the rays creates "optical confinement" (also known as "light trapping") in the module encapsulation and textured dielectric. Figure 1 illustrates some of the mechanisms by which optical coupling to the photovoltaic cell is enhanced with the textured-dielectric film in a module. Rays reflected at the glass-dielectric interface (Ray 1) are incident upon the glass-air interface; many of these rays (around 53%) experience total internal reflection at the glass-air interface. Similarly, many of the rays reflected at the dielectric-silicon interface experience

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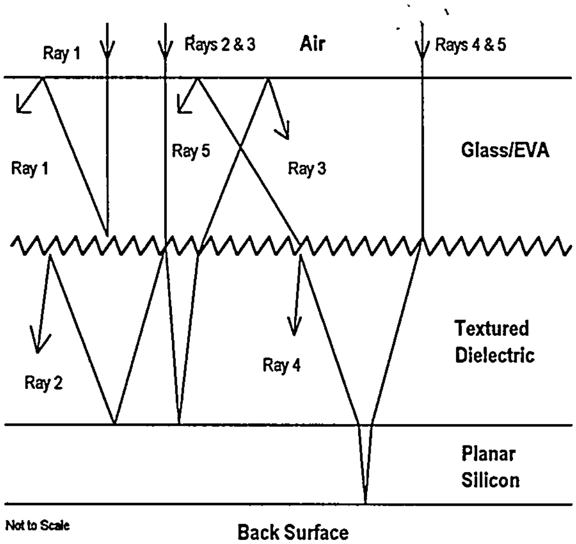

Figure 1. Illustration of the optical structure of an encapsulated photovoltaic module with a planar solar cell and textured-dielectric coating.

total internal reflection either at the dielectric-glass interface (60 to 70%, Ray 2) or, if transmitted at the dielectric-glass interface, at the glass-air interface (53%, Ray 3). Finally, light not absorbed in the silicon (i.e., "escape reflectance") is transmitted back into the textured dielectric; these rays behave similarly to the rays reflected at the dielectric-silicon interface, so that many of these rays experience total internal reflection either at the dielectric-glass interface (60 to 70%, Ray 4) or, if transmitted into the glass, at the glass-air interface (53%, Ray 5). The net result of the mechanisms illustrated with Rays 1, 2, and 3 is a reduction in "external" reflectance of the *encapsulated* silicon solar cell. The net result of the mechanisms illustrated with Rays 4 and 5 is to enhance the optical absorption of the silicon by providing multiple chances for absorption, which is similar to the "light trapping" effect in textured silicon cells [6].

OPTICAL MODELLING

We developed an optical model of a crystalline-silicon module and applied the model to three types of crystalline-silicon modules: (1) a textured silicon cell with a SLAR coating; (2) a planar silicon cell with a textured-dielectric coating (TDC); and (3) a planar silicon cell with a SLAR coating. Details of the optical model are described in the Appendix, and results of the calculations are presented in Table 1.

The textured-dielectric coating is very effective in both reducing reflectance losses and increasing optical absorption through optical confinement in the module. The active-area solar-weighted reflectance is reduced by over a factor of two for the planar-silicon cell with TDC compared to the planar-silicon cell with SLAR coating, which is the present standard commercial product. In addition, the short-circuit current densities of the textured-dielectric and textured-silicon modules are very similar.

The most important parameters for optimization of textured-dielectric coatings are (1) reflectance at the glass-textured dielectric interface and (2) the refractive index of the textured dielectric (Figure 2). Reflectance at the glass-textured dielectric interface is important because 53% of the light reflected at this interface escapes the module at the glass-air interface. A larger refractive index for the

Table 1: Calculated active-area short-circuit current density (J_{sc} in mA/cm^2) and solar-weighted reflectance (<R> in %) of c-Si photovoltaic modules with three different structures. Active-area means that grid reflectance was not included in the calculations, although the calculations included the reflectance at the air-glass interface. Calculation of J_{sc} assumed unity internal quantum efficiency. These calculations used optimistic parameters for the textured-dielectric coating (TDC), including a refractive index of 2.6 and double-bounce reflectance at the glass-TDC interface.

	Textured Si with SLAR	Planar Si with TDC	Planar Si with SLAR
J_{sc}	40.4	39.6	37.0
<R>	5.0	6.3	14.3

textured-dielectric coating improves optical confinement in the textured dielectric, but can also increase reflectance at the glass-textured dielectric interface. Our application requires a refractive index greater than 2 for the textured-dielectric coating (Figure 2).

EXPERIMENTAL RESULTS

We experimentally confirmed the physics of our concept and of our optical models using thin-film diamond (TFD) coatings. These films were deposited onto silicon substrates by chemical vapor deposition (CVD). While CVD diamond is probably too expensive for solar cells, the TFD films are ideal for testing our optical model because these films are highly faceted (Figure 3) and have a large refractive index (around 2.4). We measured the hemispherical reflectance of as-deposited and of encapsulated TFD-coated silicon samples, and fitted the data with our optical model (Figure 4). The only adjustable parameter in the model is the fraction of single- and double-bounce reflectance at the glass-TFD interface, which is not *a priori* known without a detailed description of the geometrical distribution of the diamond crystals. The agreement between the data and our model is excellent, with the fraction of reflectance at the glass-TFD interface due to double bounce around 30%.

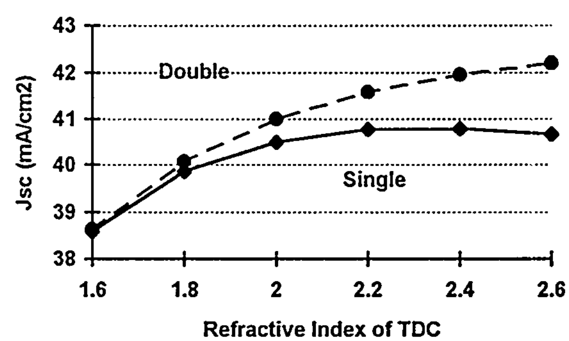

Figure 2. The effect of varying the refractive index of the textured-dielectric coating (TDC) and of the reflectance at the glass-TDC interface. "Single" and "double" refer to the number of bounces a ray experiences before reflecting from the glass-TDC interface. Hence, reflectance at the glass-TDC interface is much lower for double-bounce than for single-bounce reflectance.

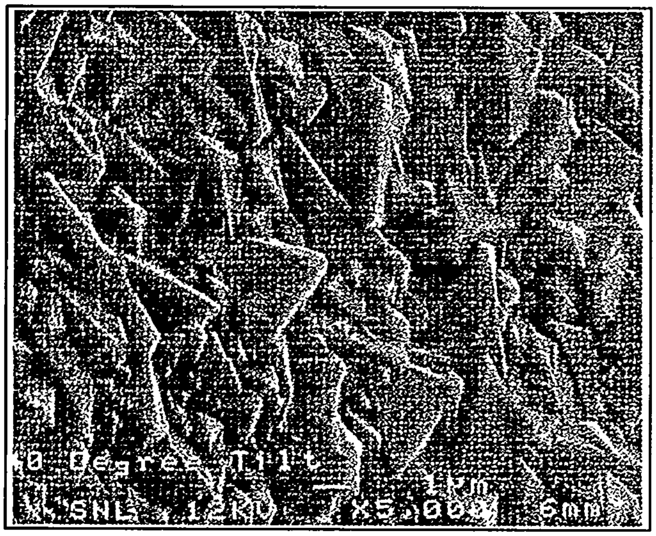

Figure 3. SEM photomicrograph of surface of thin-film diamond that was deposited by chemical vapor deposition on a silicon wafer.

The solar-weighted reflectance of the encapsulated TFD-silicon sample is only around 7.3%. This value is around one-half the active-area solar-weighted reflectance of a typical mc-Si module (planar cell with SLAR - see Table 1) despite the fact that the TFD film was not optimized for our application. The module reflectance could be further reduced with either an antireflection coating over the TFD film or optimization of the TFD deposition so that more rays experience double-bounce reflectance at the glass-TFD interface.

We also evaluated textured-ZnO films on silicon wafers. These films were deposited by atmospheric-pressure chemical vapor deposition in a belt furnace. These films had a slightly higher reflectance after encapsulation compared to the encapsulated TFD-coated silicon samples, which is probably due to the lower refractive index of ZnO (n=2.0).

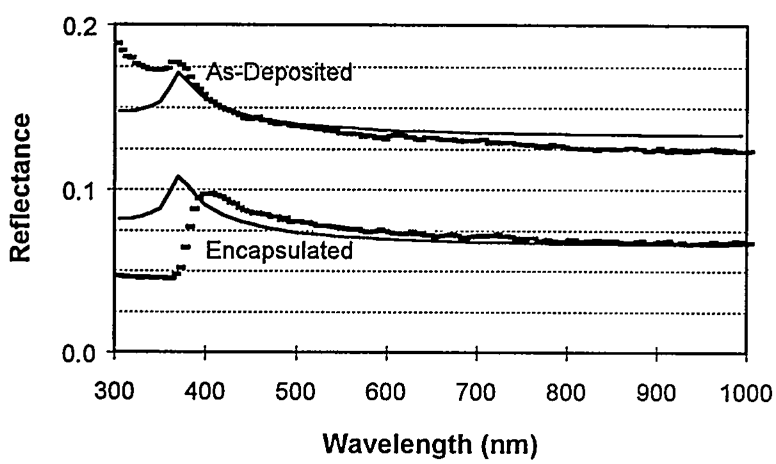

Figure 4. Hemispherical reflectance of silicon wafer coated with thin-film diamond before and after encapsulation. Model fit is solid line and data is dashed line.

DISCUSSION AND SUMMARY

Light-trapping geometries for increasing the optical absorptance of solar cells may be classified into two categories -- internal confinement, where the optical confinement occurs internally in the solar cell due to scattering at the cell's surfaces, and external confinement, where the optical confinement occurs external to the cell in external cavities [7]. Use of the module encapsulation for reflectance control is therefore a type of external confinement [7]. External confinement has generally been examined for use as either an optical concentrator or for increasing the optical absorptance of the solar cell. This paper, however, demonstrates that external confinement is also useful for controlling reflectance. The use of the textured-dielectric coating should also allow the use of thinner mc-Si cells, although we did not examine this possibility in this paper.

Textured-dielectric coatings have several practical advantages compared to other approaches for controlling reflectance in mc-Si modules. Suitable materials for the textured-dielectric coating include ZnO, TiO_2, and SnO_2; these materials have large refractive indices (n>2) and have been deposited with textured surfaces and with low-cost technologies [5]. The textured-dielectric coating introduces no complications in the cell process if the coating is applied after the grid metallization. In contrast, mechanical texturing produce surfaces with large texture dimensions that can significantly complicate the cell fabrication process [9]. In addition, a TDC deposited over the grids should reduce grid obscuration losses by recovering reflected light from the grid through optical confinement in the module encapsulation.

In conclusion, we presented a new method for reducing the reflectance and improving the optical absorptance of photovoltaic modules using textured-dielectric coatings. The new method is useful with planar-surface solar cells (e.g., mc-Si) and has potential cost and performance advantages over other reflectance-control approaches for mc-Si solar cells.

APPENDIX: OPTICAL MODEL OF A c-Si PHOTOVOLTAIC MODULE

A c-Si photovoltaic module typically has the silicon solar cell encapsulated under glass with a polymeric material. The glass and polymeric material (generally ethylene vinyl acetate - EVA) have very similar refractive indices, so that the optical interface between the EVA and glass may be ignored in optical models. An illustration of the model is presented in Figure A1. The model consists of four optically thick layers. The first layer (Layer 0) is the incident optical medium; i.e., Layer 0 is air with a refractive index of 1. Layer 1 is the encapsulant (glass/EVA) and has a refractive index of 1.50. Layer 2 is the textured-dielectric film with a high refractive index. Layer 3 is the silicon cell and is characterized with both a refractive index and an absorption coefficient.

We define an effective intensity for forward and backward traversing waves in each layer (I_i^+ and I_i^-). Each interface is characterized by a reflectance and transmittance coefficient. Layer 3 is further characterized by an effective per-pass bulk transmittance (T_b) and a back-surface reflectance (R_b). T_b is a function of the absorption coefficient and the cell

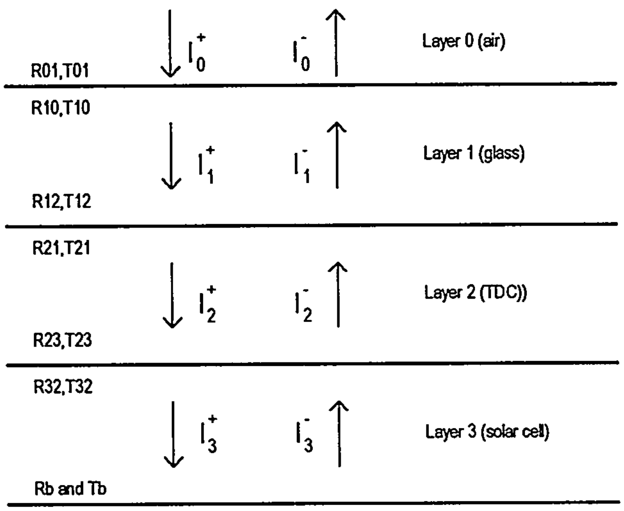

Figure A2. Illustration of the thick-film optical model of a photovoltaic module. TDC is textured-dielectric coating.

width. The resulting set of algebraic equations are solved by elimination. Krauter *et alia* recently described a similar optical model of one-sun photovoltaic modules that includes non-normal incidence and polarization effects [9].

The optical model is relatively straightforward while the physics of the model is embedded in the interfacial reflection and transmission coefficients (R_{ij} and T_{ij}). We assume no absorption at an interface, so T_{ij} is equal to 1 minus R_{ij}. For a planar interface, reflectance at the i-j interface R_{ij} is equal to the reflectance at the j-i interface R_{ji} due to symmetry of the Fresnel equations, which leads to minimal optical confinement in Layer j. For a textured interface, we assume that both the reflected and the transmitted rays are completely randomized. For example, assume that medium j has a higher refractive index than medium i. For a textured interface, the reflectance at the i-j interface (rays incident from the Layer i) can be very small, particularly if we assume that the rays undergo "double bounce" or if the interface includes a thin-film antireflection coating. On the other hand, the reflectance at the j-i interface can now be quite high due to the assumption of randomized rays inside medium j and to total internal reflection at the j-i interface. In the limit of complete randomization of the direction of rays, the percentage of rays reflected by total internal reflection at the j-i interface is given by the following expression [6]:

$$R_{ji}=1-T_{ij}/(n_{ji})^2 \quad \text{and} \quad n_{ji}=n_j/n_i$$

The bulk transmittance T_b in the silicon depends upon the assumed distribution of rays. For a planar silicon cell with incident parallel rays, the rays have uniform directions and traverse the silicon perpendicular to the surfaces. The absorption of these rays is simply expressed with an exponential function ($\exp(-\alpha w)$). For the textured silicon cell, the rays are assumed to be randomized similar to conventional light-trapping calculations [6]. For the case of a textured dielectric with a planar dielectric-silicon interface, the rays transmitted into the silicon subtend an angle of double the critical angle at the silicon-dielectric interface. This angle is about 94° for a refractive index of 2.6 for the dielectric film and a refractive index of 3.55 for silicon. For either the textured silicon or the textured dielectric cases, the transmittance is an integral over the distribution of rays [10].

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