

Electrophoretic deposited TiO₂ pigment-based back reflectors for thin film solar cells

Braden Bills,^{1,2,*} Nathan Morris,¹ Mukul Dubey,² Qi Wang³ and Qi Hua Fan^{2,1}

¹Applied NanoFilms, 2301 Research Park Way STE 217, Brookings, SD 57006, USA

²Department of Electrical Engineering and Computer Science, South Dakota State University, Brookings, SD 57007, USA

³National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

*braden.bills@sdsu.edu

Abstract: Highly reflective coatings with strong light scattering effect have many applications in optical components and optoelectronic devices. This work reports titanium dioxide (TiO₂) pigment-based reflectors that have 2.5 times higher broadband diffuse reflection than commercially produced aluminum or silver based reflectors and result in efficiency enhancements of a single-junction amorphous Si solar cell. Electrophoretic deposition is used to produce pigment-based back reflectors with high pigment density, controllable film thickness and site-specific deposition. Electrical conductivity of the pigment-based back reflectors is improved by creating electrical vias throughout the pigment-based back reflector by making holes using an electrical discharge / dielectric breakdown approach followed by a second electrophoretic deposition of conductive nanoparticles into the holes. While previous studies have demonstrated the use of pigment-based back reflectors, for example white paint, on glass superstrate configured thin film Si solar cells, this work presents a scheme for producing pigment-based reflectors on complex shape and flexible substrates. Mechanical durability and scalability are demonstrated on a continuous electrophoretic deposition roll-to-roll system which has flexible metal substrate capability of 4 inch wide and 300 feet long.

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OCIS codes: (350.6050) Solar energy; (290.5850) Scattering, particles; (310.0310) Thin films.

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1. Introduction

Highly reflective coatings with strong light scattering effect have many applications. Thick films of BaSO₄ particles have long been used in integrating spheres in spectrophotometers for calibrating reflectance. Recently, pigment-based reflectors with high refractive index pigments in a low refractive index media attracted great interests for improving solar cell efficiency and stability. A pigment reflector is particularly appealing for lightweight and flexible solar cells due to its environmental stability and strong scattering characteristics.

Thin film silicon (Si) solar cells are attractive photovoltaic devices for energy conversion due to the abundance of Si feedstock, non-toxicity, low susceptibility to moisture leading to fewer encapsulation challenges, and substantial synergies with the flat panel display market [1]. Thin film Si solar cells consist of amorphous and microcrystalline materials in single or multi-junction configurations, which typically have thickness of a few hundred nanometers and a few microns, respectively. Substrate configured thin film Si solar cells have additional advantages such as low-cost, roll-to-roll manufacturing using inexpensive metal web substrates, which are applicable to flexible, lightweight niche markets. High efficiency and low cost thin film Si solar cells have electrically "thin" and optically "thick" device structures, which is achieved by using back reflectors to maintain high light absorption while decreasing Si film thickness. This improves material stability, increases the electric field across *pin* junction, and lowers deposition times [2]. Current substrate configured thin film Si solar cell back reflectors consist of sputtered aluminum (Al) or silver (Ag) with sputtered polycrystalline zinc oxide (ZnO) buffer layer. Record high efficiencies for thin film Si solar cells have been all achieved using Ag/ZnO back reflectors, but currently these are not used in commercial production due to cost, Ag migration, oxidation, and adhesion reliability [3–7]. Instead, Al/ZnO back reflectors are used, which meet reliability criteria but have lower reflection in the critical 600 nm to 900 nm wavelength range, resulting in significantly lower photocurrent and efficiency compared to Ag back reflectors.

Pigment-based back reflectors were recently shown to improve photocurrent for glass-based superstrate configured Si solar cells [8–14]. The most common pigment material is titanium dioxide (TiO₂) particles with a typical diameter of a few hundred nanometers and is commercially available from companies such as DuPont. However, white paint pigment-based back reflectors are not suitable for use with substrate configured solar cells, where the back reflector is deposited on the substrate first. The organic medium of white paint cannot withstand high vacuum, high temperature and plasma processing conditions of Si absorber and transparent conductive oxide layer depositions. Further, pigment-based (white paint) back reflectors were not conductive.

This paper presents the optical performance of pigment-based reflector films without organic medium. Chemically stable TiO₂ pigment was chosen since it can withstand harsh absorber layer processing conditions and avoids the reliability issues associated with Ag and

to a lesser extent Al metals. Pigment-based films were fabricated by a unique electrophoretic deposition (EPD) process, which has the advantages of rapid, large-area deposition of films with high pigment packing density and controllable thickness at a low-cost. Diffuse and total reflection spectra of pigment-based back reflectors were compared with conventional Ag/ZnO and Al/ZnO back reflectors. The effect of back reflectors on solar cell performance was compared using a setup of placing back reflectors directly behind a semi-transparent amorphous Si solar cell. This work also demonstrates making pigment-based back reflectors electrically conductive by creating electrical vias throughout the film by first, generating holes using an electrical discharge method, and second, using the site-selective properties of EPD to refill the holes with conductive nanoparticles. Engineering the morphology of nanoparticle-based films using the electrical discharge method is, to the authors' knowledge, a new approach. Mechanical durability of pigment-based reflector coatings was characterized. A pilot roll-to-roll process validated a pathway to realizing large-area fully functional components and devices, such as the direct deposition of solar absorber layer onto pigment-based back reflector.

2. Theory of pigment-based diffuse back reflectors

Figure 1 illustrates a basic ray-tracing schematic of a typical pigment-based back reflector for substrate configured thin film solar cell. The substrate is coated with densely packed pigment (e.g. TiO₂) film with medium (e.g. air) and subsequently coated by solar absorber material (e.g. amorphous Si) and front transparent contact. The pigment-based back reflectors of this work differ from previous [8–13] in that they consisted entirely of pigments without an organic medium, such that the pigments were in direct contact with each other and not dispersed in an organic medium. Incident light that is unabsorbed by the initial pass through solar absorber is reflected back into the solar absorber by the pigment-based back reflector.

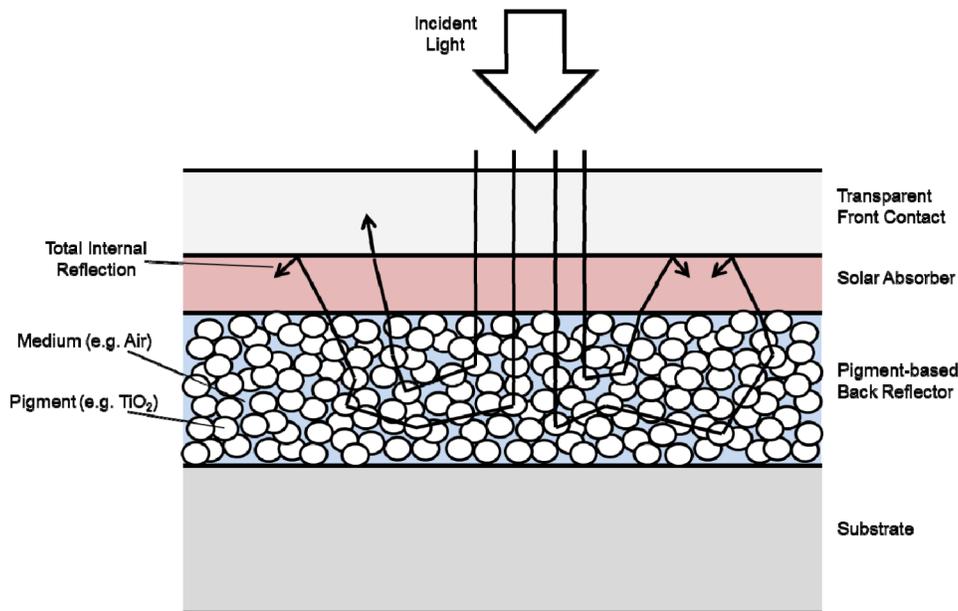


Fig. 1. Ray-tracing schematic of pigment-based back reflector.

Light is reflected in a diffuse pattern due to multiple Mie scattering and Fresnel/Snell refraction/reflection events resulting in light reflected into the solar absorber at wide angles compared to normal, which has the benefit of increasing distance of reflected light through absorber layer and light can be reflected back into the absorber multiple times via total

internal reflection at the absorber / front transparent contact interface. This light trapping enhancement, Z , is dependent on refractive index and quantified by

$$Z = 4 \frac{n_{abs}}{n_{abs} + \sqrt{n_{abs}^2 - n_{BR}^2}} n_{BR}^2 \quad (1)$$

where n_{abs} and n_{BR} are the refractive indices of solar absorber, e.g. ~ 3.6 for amorphous Si, and back reflector, respectively, where the maximum enhancement, i.e. the Yablonovitch limit, of $Z = 50$ is obtained when $n_{BR} = n_{abs}$ [1, 14–16]. For pigment-based back reflector without organic medium, n_{BR} is somewhere between that of TiO₂ pigment (~ 2.7) and air (~ 1). Assuming spherical TiO₂ pigments in a film with high packing density analogous to a body centered cubic unit cell then 68% and 32% of the cubic volume would consist of pigment and air, respectively, which results in Bruggeman effective n_{BR} of ~ 2.1 and Z enhancement of $\sim 9.7x$ for amorphous Si solar cells [17]. Similar n_{BR} (~ 2) and Z ($\sim 9x$) values for higher crystallinity thin film Si ($n \sim 3.5$) were shown in [14].

Reflectance from the bulk, R_{Bulk} , of the pigment-based back reflector is independent of the substrate and solar absorber material properties and for a sufficiently thick pigment-based back reflector is described by

$$R_{Bulk} = 1 + \frac{K}{S} - \sqrt{\frac{K}{S} \left(\frac{K}{S} + 2 \right)} \quad (2)$$

where K is the absorption coefficient and S is the scattering efficiency of diffuse light through the pigment-based back reflector [8, 9]. Increasing bulk reflectance is achieved by maximizing the scattering efficiency and minimizing the absorption coefficient, such as by the use of wide band gap materials, e.g. TiO₂. Scattering of light by spherical particles, i.e. pigments, was described by Mie and is dependent on three parameters: (1) Scattering efficiency increases by increasing the refractive index ratio between pigment and medium. TiO₂ pigment-based back reflectors of this work with air voids have higher refractive index ratio than pigments dispersed in organic medium, i.e. white paint, at 2.7 and 1.8, respectively, where refractive index of organic medium found in paint is typically ~ 1.5 . (2) Scattering efficiency increases with optimal pigment diameter, D_{opt} , defined by

$$D_{opt} (nm) \approx \frac{2\lambda (nm)}{\pi n_m \left(\frac{n_p}{n_m} - 1 \right)} \quad (3)$$

where λ is the wavelength, and n_m and n_p are the refractive indices of medium and pigment, respectively [18]. For example, the optimal diameter for TiO₂ pigment-based film without organic medium for 600 nm and 900 nm wavelengths would be ~ 224 nm and ~ 337 nm, respectively. The DuPont R900 TiO₂ pigments have an irregular spheroid shape and size distribution of a few hundred nanometers averaging at 410 nm to ensure a broadband reflection and scattering. (3) Scattering efficiency is maximized at intermediate pigment concentrations; that is, scattering efficiency increases with increasing pigment concentration until multiple scattering events begin to hinder reflection and after an intermediate pigment concentration the scattering efficiency begins to decrease back to zero [8, 9]. Pigment-based back reflectors of this work have high packing density, which may result in higher pigment concentration than optimal in terms of scattering efficiency; though this may be offset by an increased Z enhancement (Eq. (1)).

In addition to enhanced light reflection and light scattering, back reflectors for substrate configured solar cells must be sufficiently conductive; otherwise, they may increase the series resistance thereby decreasing the performance of the solar cell. For Ag/ZnO and Al/ZnO back

reflectors, the series conductivity is limited by the resistance through ZnO from absorber to metal substrate. Polycrystalline ZnO is needed to enhance conductivity and the thickness is optimized such that the competing needs of preventing metal ion migration (thick) and reducing resistivity (thin) are met. The need for polycrystalline ZnO has the consequence of slower deposition rate as well. Similarly, pigment-based back reflectors need to have sufficient series conductivity.

3. Experimental

The EPD method was chosen to fabricate pigment-based back reflector films since it can deposit thick films in a relatively short amount of time while maintaining conformal uniformity and high packing density. A pigment solution was prepared by mixing DuPont R900 TiO₂ pigment with a spin-on-glass blend (SilicAR LS-800S, Industrial Science and Technology Network) in a 1 g / 10 mL ratio. The approximate percent weights of the spin-on-glass blend components were: 1-25% of polysiloxane; 50-98% of isopropyl alcohol, ethyl alcohol and ethylene glycol butyl ether; 0-5% hydrochloric acid or nitric acid; with the remainder water [19]. The pigment solution was stirred and sonicated for up to 10 minutes. Substrates were either 6061 polished aluminum (McMaster-Carr) or 6 mil thick 430 stainless steel foil (McMaster-Carr) in 1 inch by inch, 2 inch by 8 inch, or 4 inch by 10 feet size. Metal substrates were used as electrodes in the EPD setup with 1.5 cm spacing, and the pigment-based back reflector was deposited on the negative electrode. A constant 200 V was applied to the electrodes for 1 second to 90 seconds to vary the pigment-based film thickness. All depositions were carried out at room temperature.

Additional film engineering was also performed, such as hole formation in pigment-based film and deposition of a second layer of nanoparticles into the holes. Formation of holes in pigment-based back reflector film was accomplished using high voltage electrical discharge between two asymmetrical electrodes [19]. One of the electrodes was the substrate of the pigment-based film and was connected to ground. The other electrode was a very thin wire, e.g. 40 gauge, placed parallel to the ground electrode with about 4 cm spacing. Negative 10 kV was applied to the thin wire which caused dielectric breakdown of air creating a spark between the wire and substrate, hence through the pigmented back reflector film creating a hole. Multiple electrical discharges occurred across the length of the thin wire resulting in hole formation across the entire film as the ground electrode was moved with respect to the thin wire at a constant rate. Holes were subsequently filled with 20 nm to 70 nm indium tin oxide (ITO) nanoparticles (US Research and Nanomaterials) using similar procedures as TiO₂ pigment-based films, except that an applied voltage of 100 V for 5 seconds was used.

Reflection measurements were done by a Shimadzu UV-2600 spectrophotometer with integrating sphere attachment using BaSO₄ powder reference plates. Micrograph images were obtained with a Hitachi S-3400N scanning electron microscope (SEM). Solar cell fabrication and characterization were performed at National Renewable Energy Laboratory. The solar cell consisted of 0.5 cm² single junction p-i-n amorphous silicon cell fabricated by plasma enhanced chemical vapor deposition on a glass substrate. The top and bottom electrodes were sputtered ITO thin films 70 nm thick. In order to verify the performance of the back reflectors, the intrinsic a-Si absorber was made thin (~180 nm) so that the solar cell appeared semi-transparent. The illuminated current-voltage (J-V) measurements were taken under AM1.5G, 100 mW/cm² light intensity and 25°C, using an Oriel solar simulator. Sputtered Ag/ZnO and Al/ZnO back reflectors were provided by Xunlight Corporation, 3145 Nebraska Avenue, Toledo, OH 43607.

4. Results and analysis

Figures 2(a) and 2(b) show top-down and cross-section SEM images, respectively, of TiO₂ pigment-based films with 20 second deposition time. The pigment-based films had a high pigment packing density and conformal uniformity. Pigments were approximately ~200 nm to

~500 nm in diameter. Cross-section SEM at a section of film lifted off of substrate further showed the compactness of the pigment-based film and uniformity of the film thickness, which was approximately 23 μm for a 20 second deposition time.

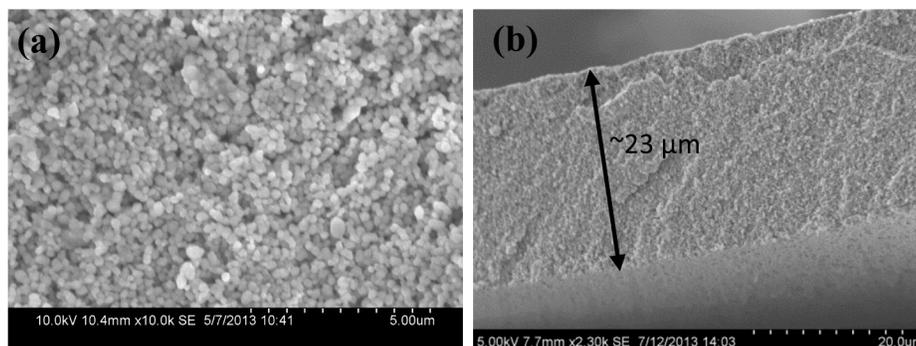


Fig. 2. SEM images of (a) top-down and (b) cross-section of typical 410 nm TiO_2 nanoparticle-based back reflector film for 20 second deposition time.

Broad spectrum (200 nm to 1400 nm) diffuse, i.e. scattered, reflection of the pigment-based films at increasing deposition times and thickness are shown in Fig. 3. The pigment-based films do not reflect ultraviolet (< 400 nm) light due to bandgap absorption of rutile TiO_2 , which has a typical band energy of 3.2 eV. A diffuse reflection maxima of 82~84% was observed at 448 nm and a relatively linear decrease to 69~77% at 1400 nm for films with deposition times of 10 seconds and longer. The pigment-based film with 1 second deposition had a maximum diffuse reflection of 60% obtained at both 424 nm and 1400 nm and reflection minimum at 818 nm wavelengths, where the reflection minimum was believed to be due to intrinsic absorption of the underlying polished Al substrate. Overall, diffuse reflection increased with increased deposition time, though the rate of increase was not linearly proportional to deposition time. The average pigment-based film thickness and deposition rate compared to deposition time are shown in the inset of Fig. 3, and indicates that the thickness and deposition rate began to saturate with increasing deposition times. This is due to the pigments being electrically insulating which increases the resistivity of the EPD electrode, i.e. metal substrate and pigment-based film, with increasing film thickness resulting in decreased deposition rate. A relatively small ($< 5\%$) difference between diffuse reflection spectra of pigment-based films with deposition times between 15 and 90 seconds, or an approximate doubling of the film thickness, signifies that pigment-based back reflector films are becoming sufficiently thick such that reflection does not significantly increase. The deposition rate of pigment-based films decreases from 2 $\mu\text{m/s}$ to 1 $\mu\text{m/s}$ for 15 second deposition and then to 0.44 $\mu\text{m/s}$ at 90 seconds, which is three to four orders of magnitude faster compared to a ZnO sputtering rate of 0.6 nm/s.

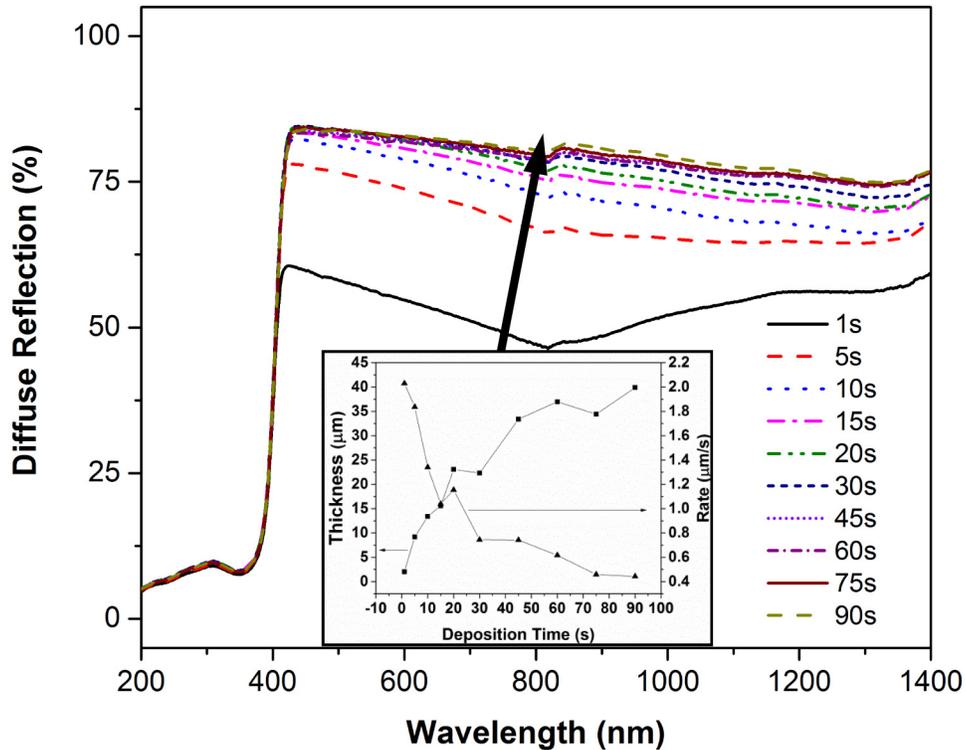


Fig. 3. Diffuse reflection of pigment-based (TiO_2 nanoparticle) back reflector with increasing deposition times and subsequently thickness. Arrow indicates increasing deposition times and thickness. Inset shows average film thickness (■) and deposition rate (▲) for each deposition time.

Figure 4 shows total and diffuse reflection of pigment-based back reflectors, conventional Ag/ZnO and Al/ZnO back reflectors, and bare stainless steel substrate. Total reflection is comprised of both diffuse and specular components. Similar to pigment-based back reflector, the Ag/ZnO and Al/ZnO back reflectors did not reflect ultraviolet light due to absorption by ZnO, which has similar bandgap energy to that of TiO_2 . The oscillating reflection spectra of the Ag/ZnO and Al/ZnO back reflectors was due to interference of light reflected at the ZnO/air interface and light transmitted through ZnO layer and reflected at Ag/ZnO interface. The total reflection spectrum of Ag/ZnO was higher than Al/ZnO from 600 to 1400 nm. The total reflection spectra of pigment-based back reflector with 90 second deposition time and approximately 40 μm thickness was higher from 400 nm to 800 nm or comparable from 800 nm to 1100 nm to Ag/ZnO. Further, the total and diffuse spectra of the pigment-based back reflector were the same, i.e. all of the reflected light was diffuse. In comparison, the diffuse reflection of the Ag/ZnO and Al/ZnO back reflectors was significantly lower than their total reflection and about a third less than pigment-based back reflector. Consequently, the amount of scattered reflected light that promotes total internal reflection in the solar absorber material was less for Ag/ZnO and Al/ZnO back reflectors. Though a broad spectrum (400 nm to 1400 nm) of light was reflected by the back reflectors, the most critical reflection region for thin film amorphous Si is 600 nm to 900 nm, where absorption is due to the band tail to opposite band transitions and the absorption coefficient is smaller. Pigment-based back reflectors had the highest reflection in this critical region. The only other reflector technology that came close was Ag/ZnO, which had only slightly higher total reflection from 800 nm to 900 nm, but significantly lower diffuse reflection throughout the entire critical region. Note that even

the 1 second deposition (2 μm thickness) shown in Fig. 3 had higher diffuse reflection than both Ag/ZnO and Al/ZnO and comparable total reflection as Al/ZnO, which took over 13 minutes to deposit.

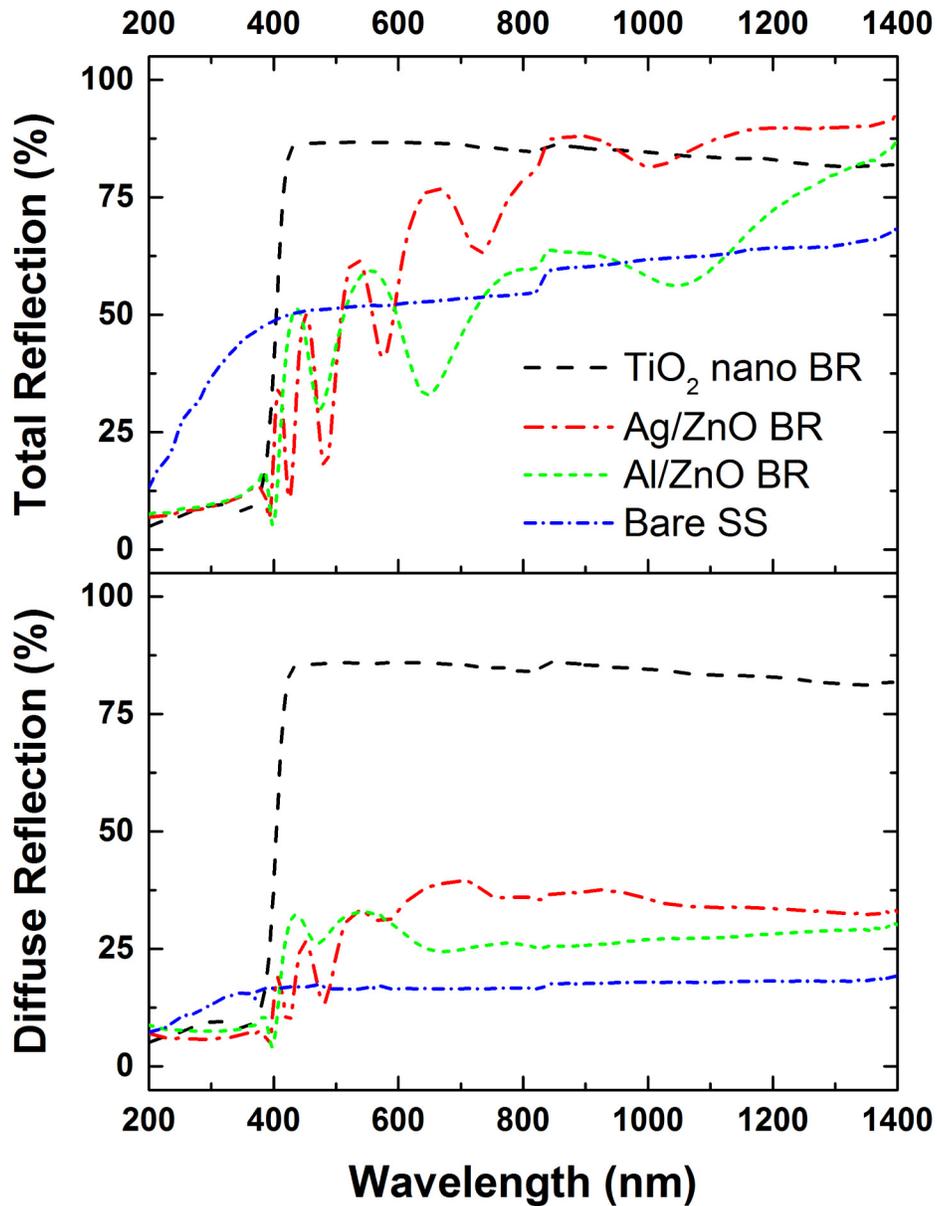


Fig. 4. (top) Total and (bottom) diffuse reflection comparison of pigment-based (TiO_2 nanoparticles) back reflector (BR) with conventional silver (Ag) and aluminum (Al) BRs with zinc oxide (ZnO) buffer layer and bare stainless steel (SS) substrate.

Solar cell performance with pigment-based and conventional metal based back reflectors was carried out by placing the back reflectors directly behind a semi-transparent amorphous Si solar cell but not electrically connected. The current-voltage characteristics are shown in Fig. 5. The table inset shows the resulting solar cell short-circuit current, open-circuit voltage, fill factor and efficiency parameters. The open-circuit voltage remained essentially unchanged

with and without each back reflector and no trends in fill factor were observed. However, incorporation of back reflectors increased the photocurrent due to an increased amount of light available for absorption and subsequent electron-hole generation. The highest photocurrent and efficiency was achieved with the pigment-based back reflector followed by Ag/ZnO and Al/ZnO which correlated with the reflection spectra of Fig. 4. That is, higher reflection spectra and higher scattering component of the pigment-based back reflector resulted in greater light trapping and solar cell efficiency enhancement compared to conventional Ag/ZnO and Al/ZnO back reflectors. Light reflection and light scattering is one parameter of many that must be optimized for fully functional back reflectors for substrate configured thin film solar cells, other parameters included electrical conductivity, surface roughness, mechanical durability and film adhesion. The remainder of this work addresses these issues.

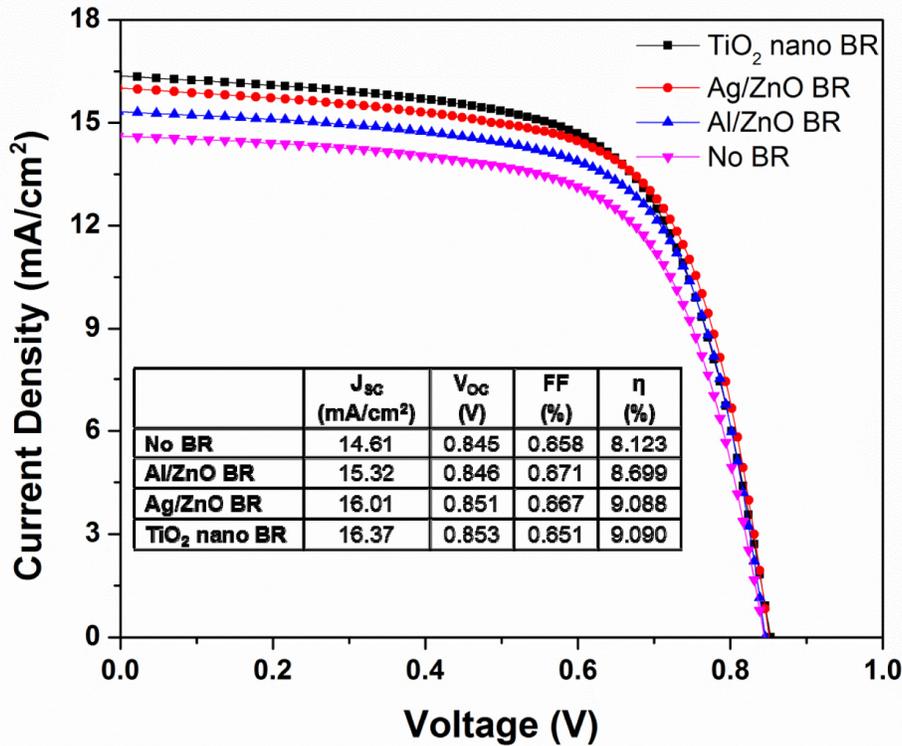


Fig. 5. Current-voltage curves of single-junction amorphous Si semi-transparent solar cell without back reflector (BR) and with conventional silver (Ag) and aluminum (Al) BRs with zinc oxide (ZnO) buffer layer and pigment-based (TiO₂ nanoparticles) BR. Table inset shows short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and efficiency (η) solar cell parameters.

Figures 6(a) and 6(b) show photograph and SEM images, respectively, of holes in the pigment-based back reflector generated by the electrical-discharge method. Hole spacing was fairly consistent at 1 mm. Increased electrical discharge time increased the hole diameter and the hole shape became less circular; electrical discharges tended to repeatedly strike the same hole location. The hypothesis of hole formation in pigment-based films by electrical discharge method was that a high temperature electrical discharge event rapidly heated the air between the pigments, i.e. the voids, causing rapid expansion of the air such that pigments exploded away from the electrical discharge strike location resulting in hole formation. Also, the high temperature melted the underlying metal substrate, which splashed up the sides of the hole

and onto the surface of the pigment-based film during the explosion of pigments. Next, the holes can be filled with conductive and non-absorbing nanoparticles to effectively act as an electrical via connecting the solar absorber layer to the underlying conductive substrate. Figure 6(c) shows a SEM image of a hole in the pigment-based back reflector filled with ITO nanoparticles by a second EPD step. The ITO nanoparticles were shown to form a mound over the hole signifying preferential deposition on the most conductive part of the film, i.e. the metal of the exposed hole and then to already deposited ITO nanoparticles. A thin film ($< 1 \mu\text{m}$) of ITO nanoparticles was formed on top of the pigment-based back reflector, though the film uniformity was poor, i.e. patchy. Resistivity of the pigment-based back reflector / hole / ITO nanoparticle films was on the order of 10^2 to $10^4 \Omega\cdot\text{cm}$. The resistivity of pigment-based back reflector without electrical discharge generated holes filled with ITO nanoparticles was too large to be measured. In comparison, the Ag/ZnO and Al/ZnO back reflectors typically have a series resistivity on the order of 10^{-1} to $10^{-2} \Omega\cdot\text{cm}$. Decreasing the pigment-based back reflector resistivity could be accomplished by thermal or photonic (e.g. Novecentrix PulseForge) curing, using a more conductive nanoparticle (e.g. metal), or reducing the pigment-based film thickness. Resistivity measurements were carried out with pigment-based film with 20 second deposition ($23 \mu\text{m}$ thickness), but as noted above even 1 second deposition ($2 \mu\text{m}$) of pigment-based back reflector had higher diffuse reflection than both Ag/ZnO and Al/ZnO. These improvements are left for future work. Finally, addition of holes and ITO nanoparticles to the pigment-based back reflector did not adversely affect the diffuse reflection, especially in the critical 600 nm to 900 nm region, as shown in Fig. 6(d). Smaller sized nanoparticles have the added benefit of smoothing the film morphology and decreasing the surface roughness in order to minimize short-circuit causing pinholes in the solar absorber layer.

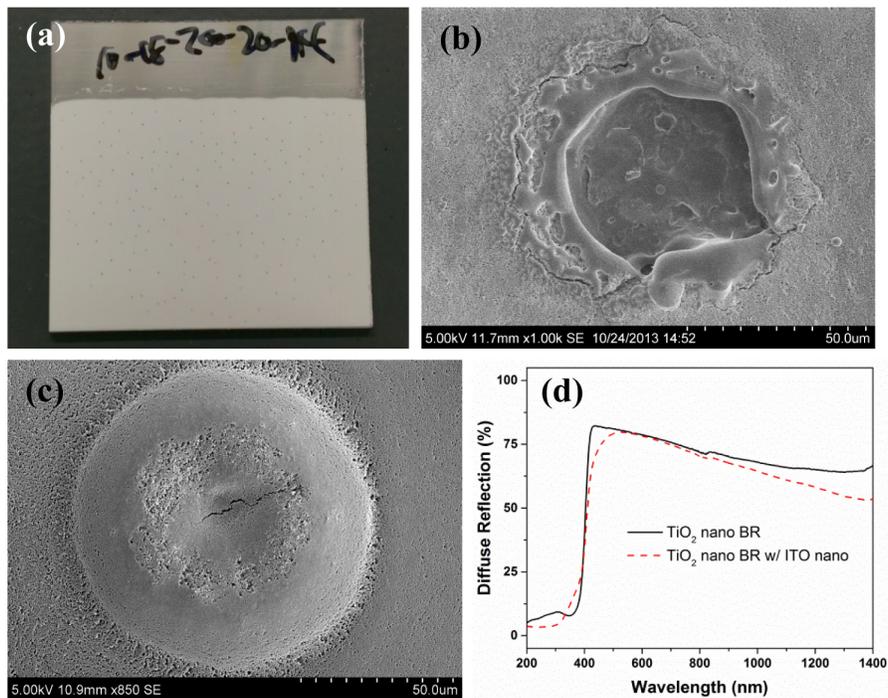


Fig. 6. (a) Photograph of pigment-based (TiO_2 nanoparticle) film with electrical discharge vias aperiodically distributed across film with about 1 mm spacing and (b) SEM image of single hole with approximately $80 \mu\text{m}$ diameter. (c) SEM image of hole in pigment-based film filled in with ITO nanoparticles and (d) diffuse reflection of pigment-based film with and without ITO nanoparticle filled holes.

Figures 7(a) and 7(b) show photographic images of pigment-based back reflectors after Scotch tape adhesion test and mechanical flexing, respectively. Scotch tape test applied to pigment-based back reflector films deposited at 20 seconds showed strong adhesion of the film to the substrate, where none of the film was peeled off by the Scotch tape and only loose pigments from scribed lines were removed by the tape. Further, a 1 inch by 8 inch pigment-based back reflector film was coated on flexible stainless steel substrate and no damage to the film, such as cracks or peeling off, was observed during flexing of the film. Promising adhesion and flexing results of the pigment-based film suggest sufficient mechanical durability to be compatible with roll-to-roll manufacturing of thin film solar cells. Figures 8(a) and 8(b) show photographic images of a continuous deposition roll-to-roll EPD system and a 4 inch wide by 6 feet pigment-based back reflector it produced, respectively. The larger pigment-based film did not show cracking or peel off damage while being flexed or rewound on the take up roller. The roll-to-roll EPD system is variable speed and can handle maximum web substrate dimensions of 4 inch wide by 300 feet long. Overall, significant progress was made towards producing highly reflective and light scattering back reflectors using chemically stable materials with strong mechanical properties, and promising scale-up potential. Additional work is needed to produce fully functional thin film Si solar cells, where the absorber layer is deposited directly onto the pigment-based back reflector. The key parameter is the surface roughness of the underlying back reflector layer, where a high surface roughness could create short circuit. While this work demonstrated that the surface roughness of pigment-based back reflectors could be partially reduced by the use of smaller sized ITO particles, additional vacuum-based or liquid-based thin films, such as ZnO, could be used to modulate the surface morphology for fully functional thin film solar cells. Optimization of the ‘smoothing’ layer(s) and fabrication of a fully functional solar cell are left as future work.

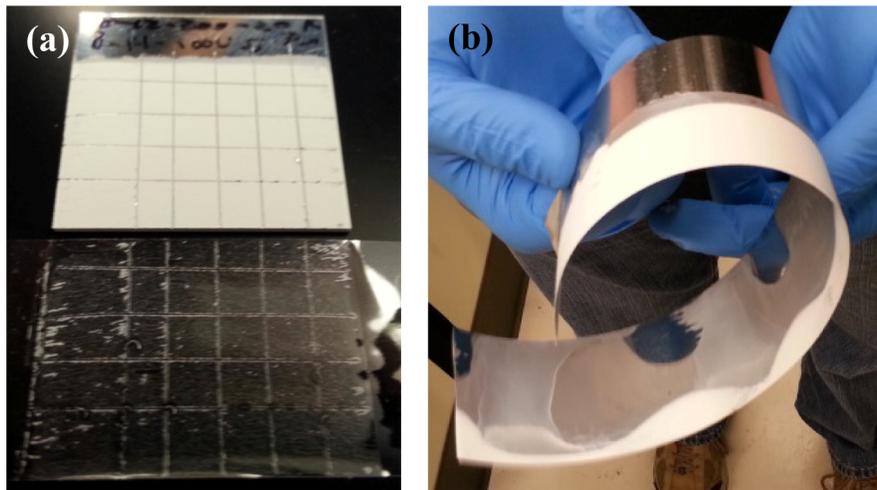


Fig. 7. Photographs demonstrating mechanical properties of pigment-based (TiO_2 nanoparticle) back reflector films with (a) scotch tape adhesion test and (b) flexing of film on flexible substrate

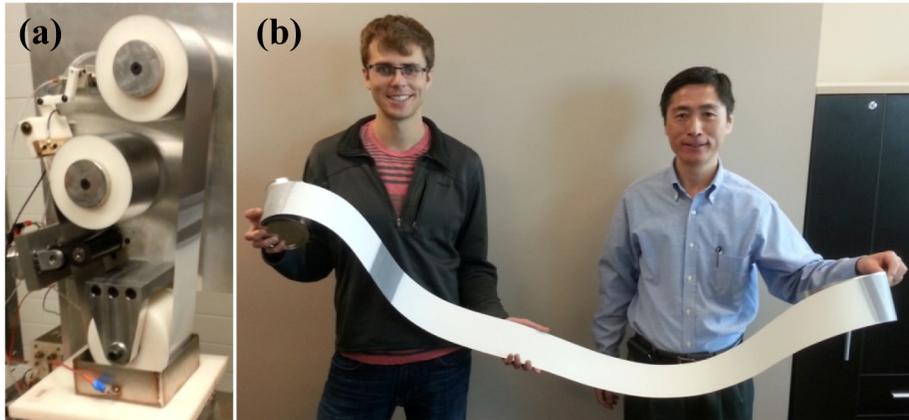


Fig. 8. Photographs demonstrating (a) continuous deposition roll-to-roll EPD system capable of handling 4 inch wide and 300 feet long metal web substrates and (b) large scale (6 feet long) pigment-based back reflector film held by researchers Bills and Fan.

5. Conclusions

Pigment-only based back reflectors produced by the EPD method were shown to have high reflection and strong light scattering capabilities resulting in enhanced thin film amorphous Si solar cell performance compared to conventional Ag/ZnO and Al/ZnO back reflectors. Back reflectors were placed directly behind the solar cell, such that only the optical qualities of the back reflectors contributed to solar cell performance. Pigment-based back reflectors were made electrically conductive by creating holes in the film by an electrical discharge method, which were subsequently filled in with transparent and conductive ITO nanoparticles. Strong film adhesion and mechanical durability were demonstrated on large-area (4 inches by 6 feet) flexible stainless steel substrates using a pilot scale continuous deposition roll-to-roll EPD system. This work shows a promising approach towards creating pigment-based back reflectors for substrate configured thin film solar cells.

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