

Research Article

Preparation and Characterization of Chitosan Binder-Based TiO₂ Electrode for Dye-Sensitized Solar Cells

En Mei Jin,¹ Kyung-Hee Park,² Ju-Young Park,³ Jae-Wook Lee,⁴
Soon-Ho Yim,⁵ Xing Guan Zhao,¹ Hal-Bon Gu,¹ Sung-Young Cho,⁶
John Gerard Fisher,⁷ and Tae-Young Kim⁶

¹ Department of Electrical Engineering, Chonnam National University, Gwangju 500-757, Republic of Korea

² The Research Institute of Advanced Engineering Technology, Chosun University, Gwangju 501-759, Republic of Korea

³ Southwestern Research Institute of Green Energy, Mokpo 530-400, Republic of Korea

⁴ Department of Chemical and Biochemical Engineering, Chosun University, Gwangju 590-170, Republic of Korea

⁵ Gist Technology Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea

⁶ Department of Environmental Engineering, Chonnam National University, Gwangju 500-757, Republic of Korea

⁷ School of Materials Science & Engineering, Chonnam National University, Gwangju 500-757, Republic of Korea

Correspondence should be addressed to Tae-Young Kim; tykim001@chonnam.ac.kr

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A chitosan binder-based TiO₂ photoelectrode is used in dye-sensitized solar cells (DSSCs). Field-emission scanning electron microscope (FE-SEM) images revealed that the grain size, thickness, and distribution of TiO₂ films are affected by the chitosan content. With addition of 2.0 wt% chitosan to the TiO₂ film (D2), the surface pore size became the smallest, and the pores were fairly evenly distributed. The electron transit time, electron recombination lifetime, diffusion coefficient, and diffusion length were analyzed by IMVS and IMPS. The best DSSC, with 2.0 wt% chitosan addition to the TiO₂ film, had a shorter electron transit time, longer electron recombination lifetime, and larger diffusion coefficient and diffusion length than the other samples. The results of 2.0 wt% chitosan-added TiO₂ DSSCs are an electron transit time of 2.189×10^{-3} s, electron recombination lifetime of 6.336×10^{-2} s, diffusion coefficient of 3.463×10^{-5} cm² s⁻¹, diffusion length of 14.81 μm, and a solar conversion efficiency of 4.18%.

1. Introduction

Since the Grätzel group discovered dye-sensitized solar cells (DSSCs), many researchers have become interested in them [1–5]. The low-cost, high-solar conversion efficiency of DSSCs is considered as a possible alternative to contemporary silicon solar cells [6, 7]. DSSCs are basically a thin layer solar cell formed by the sandwich arrangement of two electrodes, that is, a photoelectrode which is a few micron thick mesoporous TiO₂ layer coated with photosensitizer, and a platinum (Pt) coated counter electrode. The interlayer space is filled with a soluble redox couple electrolyte, such as I⁻/I₃⁻ [8–11]. TiO₂ is chemically stable, nontoxic, and readily available in vast quantities. DSSCs have many components that have to be optimized; the mesoporous TiO₂ layer is very important for increasing the solar conversion efficiency, among others [12–18]. So far, the TiO₂-based

DSSCs fabricated using multilayer (about 14 μm thickness) approaches have shown a solar conversion efficiency of 11.3%, which is lower than the theoretical maximum (33%) [19, 20]. Many researchers, in order to increase the solar conversion efficiency in DSSCs, have studied improvements to the photoelectrodes, such as the synthesis of wide band-gap TiO₂, small particle size of 10 to approximately 20 nm, large surface area of TiO₂, and increased porosity. These can increase the adsorption of the dye, and by extension, the solar conversion efficiency could be increased [21, 22].

In this present research, chitosan was adopted as a new electrode binder for DSSCs. Chitosan is a polysaccharide composed mainly of β-(1,4)-linked 2-deoxy-2-amino-D-glucopyranose units. Chitosan can be considered the most environment-friendly binder, and chitosan-based aqueous slurries possesses good viscosity and so can be considered

TABLE 1: Composition of the as-prepared chitosan sol-based TiO₂ pastes used in this study.

Sample name	Chitosan (g)	TiO ₂ (g)	Water (mL)	Acetic acid (mL)
D1	0.03	1	2	0.06
D2	0.04	1	2	0.06
D3	0.05	1	2	0.06
D4	0.06	1	2	0.06

as an effective electrode binder. We investigate natural chitosan binder-based DSSCs, describing the effect of different contents of chitosan on the activity of DSSCs. We selected for our research four amounts of 1.5 wt%, 2.0 wt%, 2.5 wt%, and 3.0 wt% of chitosan content in the TiO₂ electrode, named as D1, D2, D3, and D4 respectively.

2. Experiment

2.1. Preparation of Chitosan Sol and TiO₂ Paste. The chitosan used in this study was kindly supplied by Sehwa Co., Korea. The degree of deacetylation and molecular weight of the chitosan were 85% and 5.2×10^5 g/mol, respectively. Chitosan sol with different concentrations (1.5, 2.0, 2.5, and 3.0 wt%) were prepared by dissolving the proper amount of chitosan in 2 mL of 3% (v/v) aqueous acetic acid solution. The solution was mixed using a shaking incubator for 24 h at 250 rpm, and then the solution was left to stand for 24 h at room temperature, for complete hydration of the polymer and removal of bubbles.

The chitosan-based TiO₂ paste was prepared in the following way: nitric acid treated TiO₂ (P-25, Deagesa) power was added to 2 mL of prepared chitosan colloidal solution, and then stirring was maintained until the TiO₂ colloid was well mixed with the chitosan solution slurry. For increased dispersal of the TiO₂ paste, a three-roll mill (DEA WHA TECH., EXAKT50i) was used for about 7 h. The three-roll mill makes it possible to simultaneously mill and mix the paste. Table 1 shows the composition of chitosan sol-based TiO₂ pastes of D1, D2, D3, and D4 used in this study.

2.2. Preparation of the Photo and Counter Electrode. The prepared TiO₂ paste was cast on precleaned FTO (Pilkington FTO glass, $8 \Omega/\text{cm}^2$), using the squeeze printing method [3, 23–25]. The coated TiO₂ films were sintered at 150°C for 3 h. The active area of the TiO₂ film was 0.25 cm². The TiO₂ film was immersed into a 5×10^{-4} mol/L ethanol solution of Ru(dcbpy)₂(NCS)₂ (N719, Solaronix Co., Switzerland) overnight, then rinsed with anhydrous ethanol, and finally dried. The counter electrode was prepared using the squeeze printing technique and subsequently sintered at 450°C for 30 min. The counter electrode material was a Pt catalyst (Solaronix Co., Switzerland).

2.3. Assembly of the Testing Cells. The Pt electrode was placed over the dye-adsorbed TiO₂ electrode, and the edges of the cell were sealed. The sealing was accomplished by hot-pressing two electrodes together at 110°C. The redox

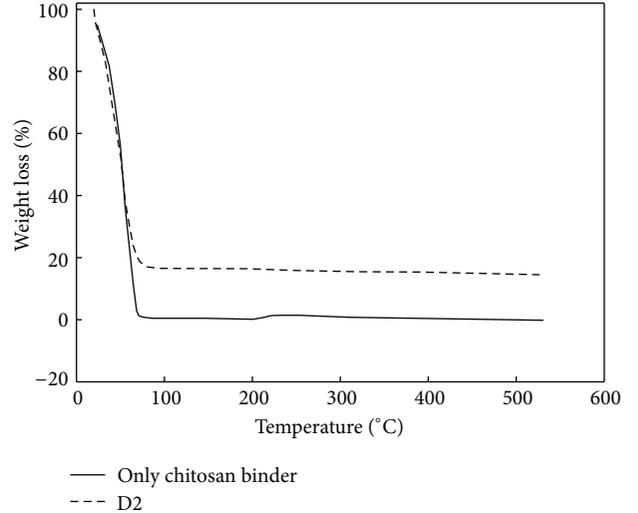


FIGURE 1: Thermal weight loss (TGA) curve of the pure chitosan sol (2.0%) and chitosan sol-based TiO₂ paste (D2).

electrolyte was injected into the cell through two small holes drilled in the counter electrode. The I⁻/I₃⁻ redox electrolyte was composed of 0.3 mol/L 1,2-dimethyl-3-propylimidazolium iodide (Sigma-Aldrich Co., USA), 0.5 mol/L 4-*tert*-butylpyridine (Sigma-Aldrich Co., USA), and 3-methoxypropionitrile. The holes were then covered and sealed, with a small square of sealing material and a microscope objective glass.

2.4. Measurements. The thermogravimetric (TGA) analyses of the chitosan sol were performed with an RIS diamond TG-DTA (PerkinElmer) analyzer. The chitosan sol was loaded into alumina pans and heated from room temperature to 530°C.

Field-emission scanning electron microscopy (FE-SEM) (Hitachi S-4700, Japan) was used to examine the film morphology, such as the surface of TiO₂ films and thickness.

The electron transit time and electron recombination lifetime were measured by intensity modulated photocurrent spectroscopy (IMPS) and intensity modulated photovoltage spectroscopy (IMVS). Blue light-emitting diodes (LEDs, 475 nm) were used as the light source. The light intensities were modulated (10%), by modulating the bias applied to the LED with sine waves, in a frequency range typically from 0.1 Hz to 1000 Hz.

The photovoltaic properties were investigated by measuring the photocurrent-voltage characteristics under illumination, with an air mass (AM) of 1.5 (100 mW/cm²) simulated sunlight. The charge transport characteristics were investigated by intensity-modulated photovoltage spectroscopy (IMVS). The IMVS was measured using red light-emitting diodes (LED, 635 nm). The light intensities were modulated by 10%, in a frequency range typically from 0.01 to 100 Hz.

3. Results and Discussion

The thermal weight loss curves for the pure chitosan sol (2.0 wt%) and chitosan sol-based TiO₂ paste (D2) are shown

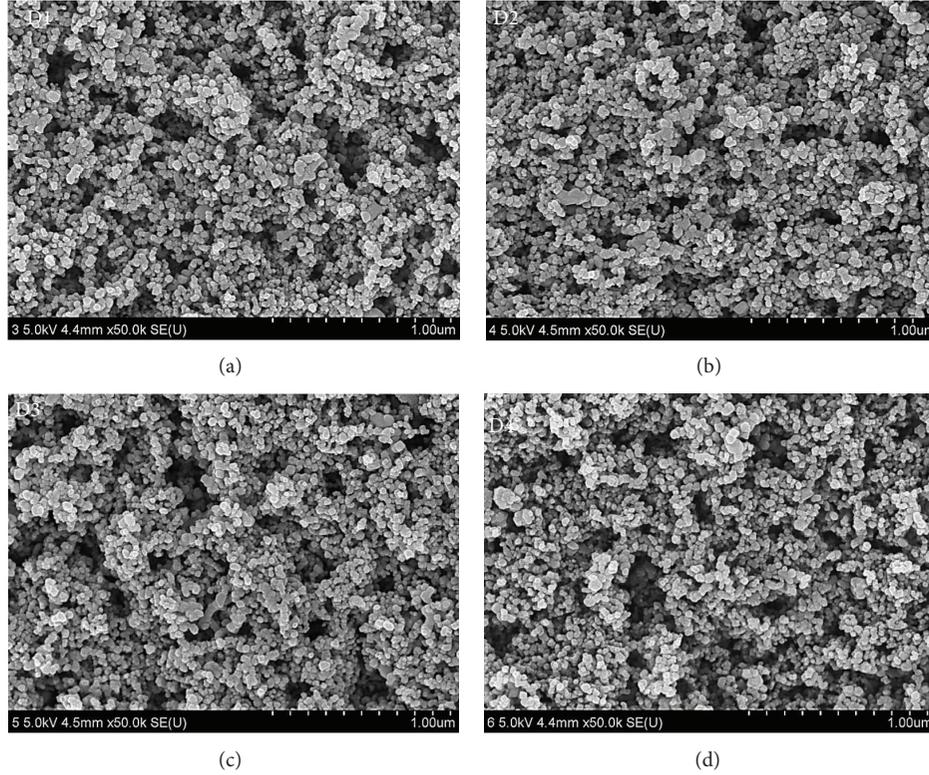


FIGURE 2: FE-SEM images of the surface morphologies of chitosan sol-based TiO_2 films.

in Figure 1. This shows that there is a large weight loss in the range from room temperature to 80°C in the TG curve, which is due to the dehydration of the pure chitosan sol and chitosan sol-based TiO_2 paste. This weight loss can be assigned to the thermal decomposition of aqueous acetic acid in the pure chitosan sol. As shown in the TGA curve of D2, we can verify that about 20 wt% residue is accurate, and the residue can be ascribed to the TiO_2 powder. So the heating temperature of the TiO_2 photoelectrode (after TiO_2 casting on the FTO substrate) can be set to be very low.

The surface morphologies of the pure TiO_2 photoelectrode and TiO_2 photoelectrode containing 1.5 wt% (D1), 2.0 wt% (D2), 2.5 wt% (D3), and 3.0 wt% (D4) of chitosan were obtained by FE-SEM and are depicted in Figure 2. As can be seen in Figure 2, the TiO_2 pastes containing different weight of chitosan could result in the TiO_2 films having different distributions of pore diameters. It was found that the TiO_2 film prepared with the D2 paste shows a smaller pore structure and that prepared with D1, D3, and D4 pastes has a larger pore diameter. The penetration of electrolyte depends on the pore size and porosity of the TiO_2 film [26]. We will investigate the influence on lifetime of the TiO_2 electrode, as well as the performance of the DSSC, by varying the amounts of chitosan content in the TiO_2 electrode.

Figure 3 shows FE-SEM images of the cross-section of chitosan sol-based TiO_2 films. In this figure, the thickness of TiO_2 of D1, D2, D3, and D4 is 6.8, 6.9, 6.8, and 6.6 μm , respectively. The solar conversion efficiency of DSSCs depends upon several factors, including the porosity, surface area, and amount of dye loading [26].

TABLE 2: Photocurrent-voltage data of the chitosan sol-based DSSCs.

Sample	Parameter			
	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
D1	0.69	9.48	58.58	3.83
D2	0.69	10.15	59.41	4.16
D3	0.68	9.59	60.35	3.94
D4	0.69	8.48	56.20	3.29

Figure 4 shows the photocurrent-voltage characteristics of different chitosan-based DSSCs. The solar cell was irradiated with a 1,000 W xenon lamp with a light intensity of 100 mA cm^{-2} as a light source. As shown in Figure 4, the D2-based DSSC has a higher solar current density than the D1, D3, and D4-based DSSCs. Table 2 shows the data of the photocurrent-voltage characteristics. The open circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), and the solar energy conversion efficiency (η) of the D2-based DSSC are 0.69 V, 10.15 mA cm^{-2} , 59.41%, and 4.18%, respectively. The η of D1, D3, and D4-based DSSCs are 3.8%, 3.95%, 3.27%, respectively. Grätzel and coworkers have reported on a highly efficient (7–11%) photoelectrochemical cell based on sensitized oxidation of iodide on a nanocrystalline TiO_2 electrode using an artificial binder [27, 28]. However, we used natural binder (chitosan) for TiO_2 paste. In comparison to the artificial binder, the efficiency of DSSCs using natural binder is not high. However, there is little data available on the use of natural binder for TiO_2 paste in the literature. Yang et al.

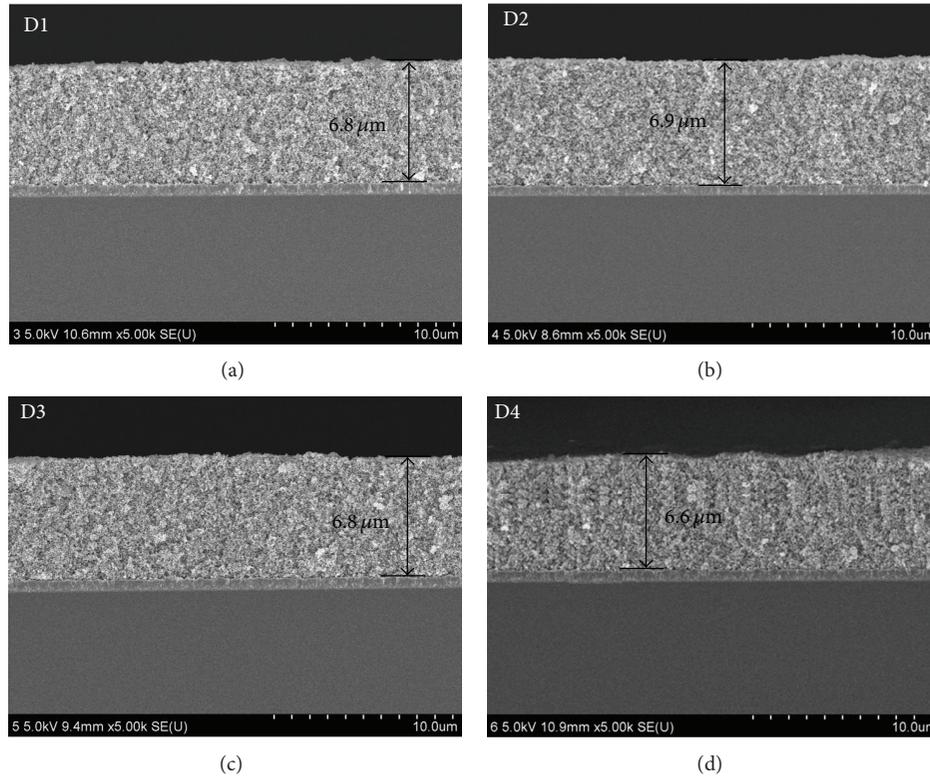


FIGURE 3: FE-SEM images of the cross-section of chitosan sol-based TiO_2 films.

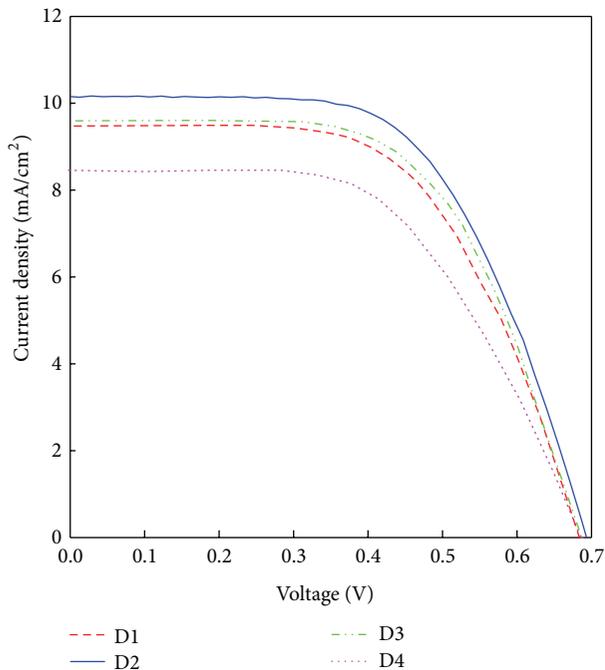


FIGURE 4: Photocurrent-voltage curves of chitosan sol-based DSSCs.

[29] reported on a DSSC with a novel Pt counter electrodes using pulsed electroplating techniques: the efficiency of DSSC was 3.85%. Deepa et al. [30] reported on efficiency

enhancement in DSSCs using metal nanoparticles: a size-dependent study; the efficiency of DSSCs range from 0.43 to 1.52. Compared to the research of Yang et al. and Deepa et al., the efficiency of DSSCs using natural binder is high. The TiO_2 photoelectrode morphology can also influence photocurrent generation. The higher efficiency of photocurrent generation has been explained by a reduction in grain boundaries, higher dye loadings, and slower recombination rates [31–35]. The electron recombination lifetimes within DSSCs are determined primarily by the recombination of electrons with iodine, electrolyte, and oxidized sensitizers. To understand the charge transport characteristics, the films were investigated by IMPS and IMVS. The electron transit time (τ_t) and electron recombination time (τ_r) can be determined using the equations $\tau_t = 1/2\pi f_{\min}$ and $\tau_r = 1/2\pi f'_{\min}$. In the equations, f_{\min} and f'_{\min} are the frequencies giving the largest imaginary components in IMPS and IMVS, respectively. The IMPS and IMVS plots are shown in Figure 5. Figure 6 displays the diffusion coefficient of chitosan-based DSSCs, and Table 3 shows the electron transport characteristic data. The electron transit time of D1, D2, D3, and D4-based DSSCs is 3.121×10^{-3} , 2.189×10^{-3} , 2.295×10^{-3} , and $4.056 \times 10^{-3} \text{ s}^{-1}$, respectively. The electron recombination lifetime of the D2-based DSSC was lower than those of the other samples. For the D2-based DSSC, the recombination lifetime is $6.336 \times 10^{-2} \text{ s}$. This result clearly indicates that electron recombination with the oxidized species is reduced in the D2 TiO_2 film. This can be understood by either looking at improvements in the network of TiO_2 nanoparticles, or at the electron behavior during transition in the D2-based

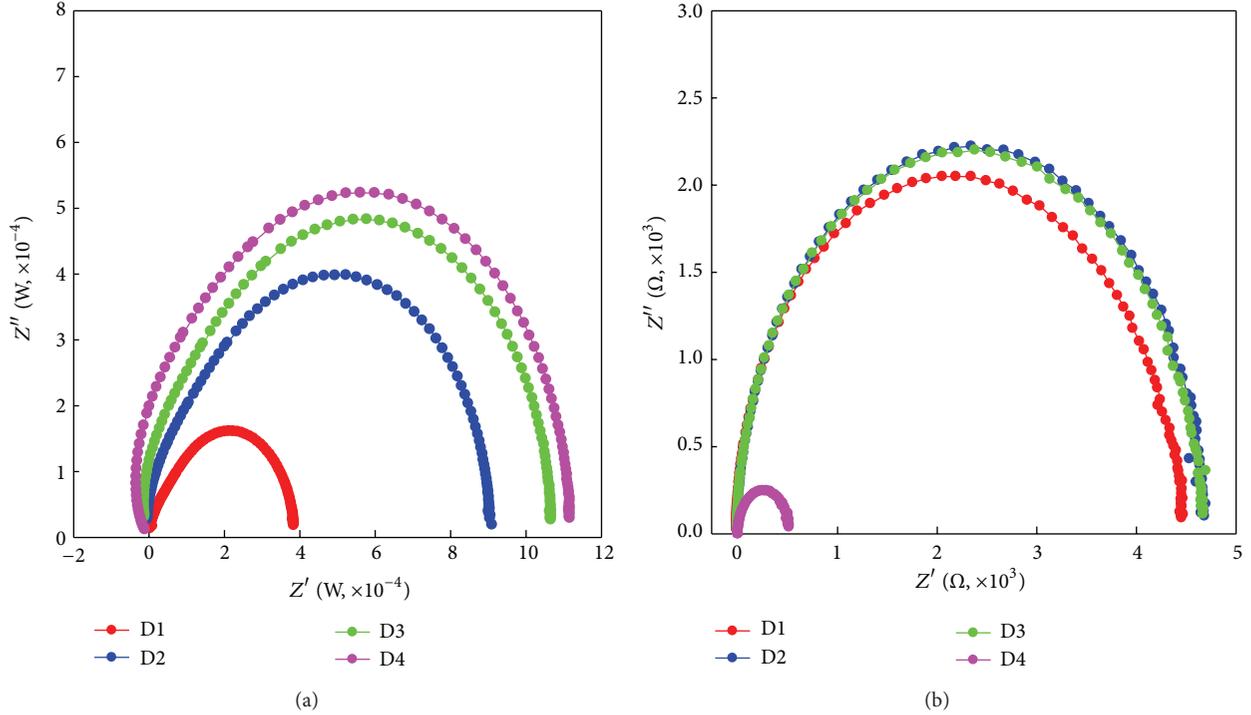


FIGURE 5: Intensity modulation photocurrent spectroscopy (IMPS) and intensity modulation photovoltage spectroscopy (IMVS) of chitosan sol-based DSSCs.

TABLE 3: Charge transport parameter of the chitosan sol-based DSSCs.

Sample	Thickness (μm)	Parameter			
		τ_t (s, $\times 10^{-3}$)	τ_r (s, $\times 10^{-2}$)	D_n ($\text{cm}^2 \text{s}^{-1}$, $\times 10^{-5}$)	L_n (μm)
D1	6.8	3.121	3.998	2.359	9.71
D2	6.9	2.189	6.336	3.463	14.81
D3	6.8	2.295	4.317	3.208	11.77
D4	6.6	4.056	2.522	1.710	6.57

TiO₂ film. From the FE-SEM, *I-V*, and electron transport characteristic results, the D2-based DSSCs have a very good film surface uniformity and high porosity. Consequently, the D2-based DSSCs have increased surface absorption and enhanced solar energy conversion efficiency.

4. Conclusions

DSSCs were fabricated using different chitosan binder sol (1.5~3.0 wt%)-based photoelectrodes. The chitosan binder sol had low calcination temperature ($\sim 150^\circ\text{C}$) and successfully prepared low temperature TiO₂ photoelectrodes. The D2 (~ 2.0 wt%)-based DSSCs had faster electron transit time and slower electron recombination time than the other samples (D1, D3, and D4). The D2-based DSSC exhibited higher solar conversion efficiencies than D1, D3, and D4-based DSSCs, because the electron recombination is more than 1.5~3 times slower in the D2-based DSSC. The electron diffusion coefficient of the D2-based DSSC was $3.463 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$,

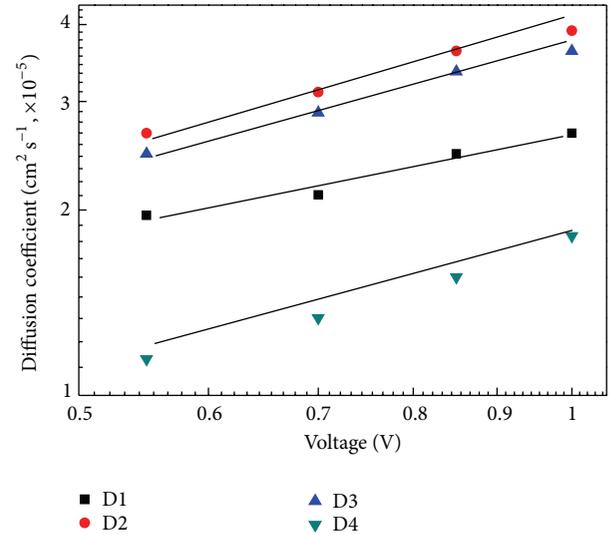


FIGURE 6: Diffusion coefficient of chitosan sol-based DSSCs.

and the diffusion length was $14.81 \mu\text{m}$. The efficiency of the D2 based DSSC was optimized to achieve 4.16% under illumination of simulated solar light, AM 1.5 global ($V_{oc} = 0.69 \text{ V}$, $J_{sc} = 10.16 \text{ mA cm}^{-2}$; fill factor is 59.41%).

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References

- [1] I. J. Kramer, A. G. Pattantyus-Abraham, A. R. Barkhouse et al., "RETRACTED: advances in colloidal quantum dot solar cells: the depleted-heterojunction device," *Thin Solid Films*, vol. 519, no. 21, pp. 7351–7355, 2011.
- [2] D. Kuang, P. Comte, S. M. Zakeeruddin et al., "Stable dye-sensitized solar cells based on organic chromophores and ionic liquid electrolyte," *Solar Energy*, vol. 85, no. 6, pp. 1189–1194, 2011.
- [3] I. K. Ding, J. Melas-Kyriazi, N. L. Cevey-Ha et al., "Deposition of hole-transport materials in solid-state dye-sensitized solar cells by doctor-blading," *Organic Electronics*, vol. 11, no. 7, pp. 1217–1222, 2010.
- [4] J. H. Yum, S. J. Moon, C. S. Karthikeyan et al., "Heteroleptic ruthenium complex containing substituted triphenylamine hole-transport unit as sensitizer for stable dye-sensitized solar cell," *Nano Energy*, vol. 1, no. 1, pp. 6–12, 2012.
- [5] G. Calogero, J. H. Yum, A. Sinopoli, G. D. Marco, M. Grätzel, and M. K. Nazeeruddin, "Anthocyanins and betalains as light-harvesting pigments for dye-sensitized solar cells," *Solar Energy*, vol. 86, no. 5, pp. 1563–1575, 2012.
- [6] B. O'Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films," *Nature*, vol. 353, no. 6346, pp. 737–740, 1991.
- [7] H. Lindström, A. Holmberg, E. Magnusson, L. Malmqvist, and A. Hagfeldt, "A new method to make dye-sensitized nanocrystalline solar cells at room temperature," *Journal of Photochemistry and Photobiology A*, vol. 145, no. 1-2, pp. 107–112, 2001.
- [8] B. Tan and Y. Wu, "Dye-sensitized solar cells based on anatase TiO₂ nanoparticle/nanowire composites," *Journal of Physical Chemistry B*, vol. 110, no. 32, pp. 15932–15938, 2006.
- [9] E. M. Jin, K. H. Park, J. J. Yun et al., "Photovoltaic properties of TiO₂ photoelectrode prepared by using liquid PEG-EEM binder," *Surface Review and Letters*, vol. 17, no. 1, pp. 15–20, 2010.
- [10] K. H. Park, H. B. Gu, E. M. Jin, and M. Dhayal, "Using hybrid silica-conjugated TiO₂ nanostructures to enhance the efficiency of dye-sensitized solar cells," *Electrochimica Acta*, vol. 55, no. 19, pp. 5499–5505, 2010.
- [11] S. Hore, C. Vetter, R. Kern, H. Smit, and A. Hinsch, "Influence of scattering layers on efficiency of dye-sensitized solar cells," *Solar Energy Materials and Solar Cells*, vol. 90, no. 9, pp. 1176–1188, 2006.
- [12] H. Pettersson, T. Gruszecki, L. Johansson, M. O. M. Edwards, A. Hagfeldt, and T. Matuszczyk, "Direct-driven electrochromic displays based on nanocrystalline electrodes," *Displays*, vol. 25, no. 5, pp. 223–230, 2004.
- [13] E. L. Tae, S. H. Lee, J. K. Lee, S. S. Yoo, E. J. Kang, and K. B. Yoon, "A strategy to increase the efficiency of the dye-sensitized TiO₂ solar cells operated by photoexcitation of dye-to-TiO₂ charge-transfer bands," *Journal of Physical Chemistry B*, vol. 109, no. 47, pp. 22513–22522, 2005.
- [14] J. Y. Lin, T. J. Chen, and C. K. Hu, "Effects of anodic titanium oxide nanotube arrays on dye-sensitized solar cells," *Journal of the Chinese Chemical Society*, vol. 57, no. 5, pp. 1176–1179, 2010.
- [15] K. Nelson and Y. Deng, "Effect of polycrystalline structure of TiO₂ particles on the light scattering efficiency," *Journal of Colloid and Interface Science*, vol. 319, no. 1, pp. 130–139, 2008.
- [16] C. S. Chou, R. Y. Yang, C. K. Yeh, and Y. J. Lin, "Preparation of TiO₂/nano-metal composite particles and their applications in dye-sensitized solar cells," *Powder Technology*, vol. 194, no. 1-2, pp. 95–105, 2009.
- [17] M. C. Kao, H. Z. Chen, S. L. Young, C. Y. Kung, and C. C. Lin, "The effects of the thickness of TiO₂ films on the performance of dye-sensitized solar cells," *Thin Solid Films*, vol. 517, no. 17, pp. 5096–5099, 2009.
- [18] F. Odobel, Y. Pellegrin, E. A. Gibson, A. Hagfeldt, A. L. Smeigh, and L. Hammarstrom, "Recent advances and future directions to optimize the performances of p-type dye-sensitized solar cells," *Coordination Chemistry Reviews*, vol. 256, no. 21-22, pp. 2414–2423, 2012.
- [19] N. Fuke, A. Fukui, A. Islam et al., "Influence of TiO₂/electrode interface on electron transport properties in back contact dye-sensitized solar cells," *Solar Energy Materials and Solar Cells*, vol. 93, no. 6-7, pp. 720–724, 2009.
- [20] C. Xu, P. H. Shin, L. Cao, J. Wu, and D. Gao, "Ordered TiO₂ nanotube arrays on transparent conductive oxide for dye-sensitized solar cells," *Chemistry of Materials*, vol. 22, no. 1, pp. 143–148, 2010.
- [21] Y. B. Tang, C. S. Lee, J. Xu et al., "Incorporation of graphenes in nanostructured TiO₂ films via molecular grafting for dye-sensitized solar cell application," *ACS Nano*, vol. 4, no. 6, pp. 3482–3488, 2010.
- [22] A. S. Nair, R. Jose, Y. Shengyuan, and S. Ramakrishna, "A simple recipe for an efficient TiO₂ nanofiber-based dye-sensitized solar cell," *Journal of Colloid and Interface Science*, vol. 353, no. 1, pp. 39–45, 2011.
- [23] A. I. Kontos, A. G. Kontos, D. S. Tsoukleris, M. Bernard, N. Spyrellis, and P. Falaras, "Nanostructured TiO₂ films for DSSCs prepared by combining doctor-blade and sol-gel techniques," *Journal of Materials Processing Technology*, vol. 196, no. 1-3, pp. 243–248, 2008.
- [24] I. Bernacka-Wojcik, R. Senadeera, P. J. Wojcik et al., "Inkjet printed and "doctor blade" TiO₂ photodetectors for DNA biosensors," *Biosensors and Bioelectronics*, vol. 25, no. 5, pp. 1229–1234, 2010.
- [25] N. Nang Dinh, N. Minh Quyen, D. N. Chung, M. Zikova, and V. V. Truong, "Highly-efficient electrochromic performance of nanostructured TiO₂ films made by doctor blade technique," *Solar Energy Materials and Solar Cells*, vol. 95, no. 2, pp. 618–623, 2011.
- [26] Y. Saito, S. Kambe, T. Kitamura, Y. Wada, and S. Yanagida, "Morphology control of mesoporous TiO₂ nanocrystalline films for performance of dye-sensitized solar cells," *Solar Energy Materials and Solar Cells*, vol. 83, no. 1, pp. 1–13, 2004.
- [27] M. Grätzel, "Photovoltaic performance and long-term stability of dye-sensitized mesoscopic solar cells," *Comptes Rendus Chimie*, vol. 9, no. 5-6, pp. 578–583, 2006.
- [28] D. Kuang, C. Klein, H. J. Snaith, R. Humphry-Baker, S. M. Zakeeruddin, and M. Grätzel, "A new ion-coordinating ruthenium sensitizer for mesoscopic dye-sensitized solar cells," *Inorganica Chimica Acta*, vol. 361, no. 3, pp. 699–706, 2008.
- [29] C. C. Yang, H. Q. Zhang, and Y. R. Zheng, "DSSC with a novel Pt counter electrodes using pulsed electroplating techniques," *Current Applied Physics*, vol. 11, no. 1, supplement, pp. S147–S153, 2011.

- [30] K. G. Deepa, P. Lekha, and S. Sindhu, "Efficiency enhancement in DSSC using metal nanoparticles: a size dependent study," *Solar Energy*, vol. 86, no. 1, pp. 326–330, 2012.
- [31] K. Fujihara, A. Kumar, R. Jose, S. Ramakrishna, and S. Uchida, "Spray deposition of electrospun TiO_2 nanorods for dye-sensitized solar cell," *Nanotechnology*, vol. 18, no. 36, Article ID 365709, 2007.
- [32] J. B. Baxter and E. S. Aydil, "Dye-sensitized solar cells based on semiconductor morphologies with ZnO nanowires," *Solar Energy Materials and Solar Cells*, vol. 90, no. 5, pp. 607–622, 2006.
- [33] M. Adachi, Y. Murata, J. Takao, J. Jiu, M. Sakamoto, and F. Wang, "Highly efficient dye-sensitized solar cells with a titania thin-film electrode composed of a network structure of single-crystal-like TiO_2 nanowires made by the "oriented attachment" mechanism," *Journal of the American Chemical Society*, vol. 126, no. 45, pp. 14943–14949, 2004.
- [34] S. H. Kang, S. H. Choi, M. S. Kang et al., "Nanorod-based dye-sensitized solar cells with improved charge collection efficiency," *Advanced Materials*, vol. 20, no. 1, pp. 54–58, 2008.
- [35] K. Zhu, N. R. Neale, A. Miedaner, and A. J. Frank, "Enhanced charge-collection efficiencies and light scattering in dye-sensitized solar cells using oriented TiO_2 nanotubes arrays," *Nano Letters*, vol. 7, no. 1, pp. 69–74, 2007.



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