Improvement in Energy Conversion Efficiency by Modification of Photon Distribution within the Photoanode of Dye-Sensitized Solar Cells

Yeon Hyang Sim,†‡ Min Ju Yun,§ Seung I. Cha,*,†‡ Seon Hee Seo,† and Dong Y. Lee†‡

†Nano Hybrid Technology Research Center, Creative and Fundamental Research Division, Korea Electrotechnology Research Institute, Changwon 51543, South Korea
‡Department of Electro-Functionality Materials Engineering, University of Science and Technology, Changwon 51543, South Korea

ABSTRACT: The dye-sensitized solar cell (DSSC) is a potential alternative to the widely used Si-based solar cell, with several advantages including higher energy conversion efficiency under weak and indirect illumination conditions, and the possibility of practical application in urban life due to their exterior characteristics. However, despite these advantages, the energy conversion efficiency of DSSCs has remained low at ~10%. To improve the efficiency of DSSCs, research has been done on modifying the materials used in DSSC component parts, such as the photoanode, electrolyte, and counter electrode. Another approach is to modify the photoanode to increase the diffusion coefficient, reduce the recombination rate, and enhance the light behavior. One of the most popular methods for improving the efficiency of DSSCs is by trapping and dispersing the incident light using a scattering layer. Use of a scattering layer has shown various interesting results, depending on the application, but it is currently used only in a simple form and there has been no deep research on the further potential of the scattering layer. In this study, the scattering center was introduced to maximize the effect of scattering. Light distribution near the scattering center, within or on the photoanode, was investigated using finite differential time domain (FDTD) numerical methods. Based on the FDTD analysis, an optimized, dome-shaped three-dimensional modified structure of a transparent photoanode with minimized scattering centers was introduced and indicated the possibility of modifying the photon distribution in the photoanode to enhance the performance of DSSCs. In addition to using the scattering center, we have introduced the structure of the dome-shaped three-dimensional structure to utilize the light distribution within the photoanode. This novel three-dimensional transparent photoanode and scattering center design increased the energy conversion efficiency of DSSCs from 6.3 to 7.2%. These results provide a foundation for investigating the role of the scattering center via further in-depth research. This new three-dimensional photoanode design provides a means to overcome the previous limitations on DSSC performance.

INTRODUCTION

The dye-sensitized solar cell (DSSC) has been developed as an affordable photovoltaic device that possesses several advantages over the widely used Si-based solar cell, including higher energy conversion efficiency under weak and indirect illumination conditions.1–3 These advantages can compensate for the weaknesses of Si-based solar cells, especially in practical applications in urban life. Additionally, DSSCs can be fabricated as flexible photovoltaic modules with various colors, suitable for building-integrated photovoltaics or electronic-integrated photovoltaics.4,5 Despite these advantages, the energy conversion efficiency of DSSCs at 1 sun, 1.5 AM has remained at ~10%, whereas that of rival technologies has increased in recent times.

In fact, there have been many efforts to increase the efficiency of DSSCs, including modifications to the photon-absorbing dye and the development of new electrolytes and counter electrodes.6–19 One method has been the modification of the photoanode, which consists of a nanoporous TiO2 film stained with a dye. The modifications have been aimed at increasing the diffusion coefficient of electrons, reducing the recombination rate, and enhancing light trapping. Among these, modification of the light distribution within the photoanode can serve as a basis for further studies. Thus, much effort has been devoted to achieving a more efficient photon distribution, in terms of energy conversion. These efforts include inserting a scattering layer on or within the photoanode, introducing photonic crystal structures, and inducing patterns.19–28
The use of a scattering layer has become the most popular method to trap light moving within the photoanode, and then disperse it within the photoanode; this allows easy modification of the light distribution via a process suitable for mass production. As a result, several optimized photoanode structures have been suggested, including a scattering layer deposited on the transparent photoanode to induce scattered light back into the photoanode, and a scattering center, generally larger TiO2 particles, within the photoanode to disperse incident light near the scattering center and prevent it passing the electrode.29,30 However, to date, the role of scattering layers has been considered from a qualitative rather than quantitative perspective. As a result, the application of scattering layers remains limited and their full potential has not yet been studied in depth.

In this study, light distribution modifications made near the scattering center within or on the photoanode were reinvestigated using finite differential time domain (FDTD) numerical methods to show the effect of a scattering layer or a scattering center on the light distribution of photoanodes in DSSCs. Additionally, based on the simulated results, three-dimensionally modified photoanode structures were developed to enhance the performance of DSSCs. The proposed structures were fabricated by a repeated screen printing process, using transparent and semitransparent TiO2 photoanodes prepared by mixing transparent photoanode paste with light-scattering particles. This process is actually similar to a previous photoanode preparation process attempted for mass production, so can be used without modification.

■ RESULTS AND DISCUSSION

The concentration of electrons generated by incident photons within a DSSC photoanode and, thus, the electrical behavior of the photoanode, can be estimated by a combination of diffusion, generation, and recombination, according to the electron continuity equation, eq 131–33

\[ D V^2 n - k(n - n_0) = G(x) \]  

Figure 1. (a) Light intensity derived from finite differential time domain (FDTD) simulation results near the single TiO2 particle in the electrolyte (refractive index = 1.4) according to TiO2 particle size and incident wavelength. (b) Light intensity near TiO2 particle of 200 nm size with different shapes including cube (left), vertical ellipsoid (middle), and lateral (right) at 500 nm incident wavelength. The incident intensity of incident light is set as unity with p-polarization and upper part of the domain is set as perfectly matched layer and the domain size is 2 \( \mu m \times 2 \mu m \).
where \( n \) is the concentration of electrons, \( n_0 \) is the concentration of electrons at the substrate and electrode, \( k \) is the recombination rate, \( G(x) \) is the generation rate, which is the gradient of light intensity, and \( D \) is the diffusivity of electrons within the electrode. As shown in this equation, \( G(x) \) can be expressed as \( \lambda I(x) \), where \( \lambda \) is the absorption coefficient of the electrode and \( I(x) \) is the light intensity, when it follows the Beer−Lambert law. Thus, the light intensity acts as source form in the linear differential equation, playing an important role in the determination of electron density and, therefore, in the performance of the electrode. Thus, to investigate the effect of light scattering, the light distribution near the scattering center should be considered.

The light intensity distribution near the scattering center, calculated by FDTD numerical methods, is shown in Figure 1a for various wavelengths corresponding to violet, green, and red, and for TiO\(_2\) particles ranging in size from 100 to 500 nm. For particles with a size finer than 50 nm, the effect of scattering is very weak (see the Supporting Information, Figure S1, for the cases of 50 and 20 nm). It is known that a shorter wavelength induces a wider and more severe scattering effect. Additionally, particle size greatly affects light distribution near the scattering center. The light intensity distribution is longitudinal when the particles become larger, as expected in Mie scattering. Furthermore, the shape of the particle also affects the scattered light intensity distribution (Figure 1b). By looking in more detail at cases with two differently oriented ellipsoids of the same size, it could be seen that the cross-sectional area intersecting the incident plane wave affects the scattered intensity. Considering the modification of light distribution by scattering, larger particles are more effective. However, larger particles occupy more volume, without producing electron generation during the operation of DSSCs. Thus, despite effective scattering of light, locating larger particles within the photoanode is not suitable. Instead, larger particles can operate more effectively when positioned outside of the photoanode, in terms of gathering light passing through into the photoanode.

The effect of particle size on photon distribution, for the photoanode on which the scattering particles are located, is shown in Figure 2. The model consists of three parts (Figure 2a): a glass substrate, a photoanode, and an electrolyte. If there is no scattering layer and the photon is absorbed in the photoanode, the light incident to the glass substrate decays vertically and exponentially according to the Beer−Lambert law, thus providing a one-dimensional photon distribution (Figure 2b).\(^{31,32}\) When large (500 nm) TiO\(_2\) particles are deposited on the photoanode in a single layer, the light scattered by the large particles is propagated to both the electrolyte and photoanode, as shown in Figure 2c. As the number of scattering particle layers increases, the photons

---

**Figure 2.** (a) Model for the calculation of light distribution in the photoanode of DSSC consisting of glass substrate (green part, soda-lime glass), photoanode (red part, refractive index = 1.9 and absorption rate = 0.12 \( \mu \text{m}^{-1} \)), and electrolyte (gray part). The lateral boundaries are all periodic boundaries. (b) Light intensity distribution in the DSSC photoanode without scattering layers or scattering centers. (c) Light intensity within the DSSC photoanode with scattering layer consisting of single layer of 500 nm sized spherical TiO\(_2\) particles. (d) Light intensity with scattering layer consisting of single layer of 200 nm sized spherical TiO\(_2\) particles. Incident light intensity is set as unity with p-polarization.
propagated into the electrolyte may rescat. The scattering layer on the photoanodes modifies the photon distribution in the electrode, so that the light intensity in the deep region of the electrode increases. Small particles (200 nm) also increase light intensity at the photoanode (Figure 2d). Considering the effect of particle size, larger particles allow for a more effective scattered photon distribution when the scattering layer is located on the top of the photoanode. This corresponds well with the results shown in Figure 1.

However, if scattering particles are used in the photoanode, volume loss due to the larger particle size compared to photoanode TiO₂ particles (∼20 nm) should be considered. To design an effective scattering effect for the photoanode, according to the results shown in Figure 1, the distribution of the particles should be considered. Thus, the use of a 100 nm scattering center (Figure S2) with an optimized photon distribution is required to obtain effective light distribution effects. To assess the actual effect of a 100 nm sized TiO₂ scattering center, the effects of 10 scattering centers in the photoanode are considered (Figure 3a), where the same model is used as in Figure 2. In this figure, more light is distributed within the electrodes than in Figure 2b, as expected. When a large scattering layer (500 nm TiO₂) is located on the photoanode, then more photons are trapped in the electrode (Figure 3d). One feature of this distribution is that a large proportion of the light is distributed outside the photoanode, and in the glass substrate, because of the scattering centers near the substrate—photoanode interface, as shown in the inset of Figure 3d. Thus, a scattering center near the interface has a negative effect on light trapping within the photoanode. To avoid this problem, the scattering centers near the interface are removed, as shown in Figure 3b,e. By removing these centers, the number of light distribution points in the photoanode can be maximized. Considering the contiguity equation (eq 1), the electrons generated near the interface can be gathered into electricity readily compared with those generated deep in the photoanode, avoiding the recombination process. Thus, a stronger light intensity near the interface, and the induction of a higher electron generation rate near the interface, could have a strong and positive effect on the performance of the photoanode. A thicker transparent layer beneath the scattering center-containing photoanode gives rise to a different photon distribution, as shown in Figure 3c,f. Compared with Figure 3b,c, in which there is no scattering layer on the photoanode, more photons are trapped in the photoanode with decreasing transparent photoanode layer thickness. However, this changes when a scattering layer is located on the photoanode (Figure 3e,f). Thus, considering the light distribution due to the scattering centers in the photoanode and scattering layer on the photoanode, the layering sequence on the substrate should be as follows: transparent layer, scattering center-containing photoanode, and scattering layer. In this case, the photons are trapped in the region of the transparent photoanode, which is located near the substrate, where the generated electrons can be gathered into electricity without loss. Additionally, the transparent layer has no volume loss because it contains no scattering centers with large TiO₂ particles. From this point of view, an optimization of the scattering center distribution

---

**Figure 3.** Light intensity distribution within the photoanode of DSSCs by scattering centers of 100 nm size are distributed (a) periodically whole range of electrode, (b) one scattering center layer absent near the interface between photoanode and substrate and (c) two scattering center layers absent near the interface between photoanode and substrate. (d)–(f) are same condition with (a)–(c) but with a 500 nm sized spherical scattering layer deposited on the photoanode, respectively. The inset shows the magnified image near the interface between the photoanode and the substrate.
should proceed according to several considerations. First, the photons should be trapped near the substrate in the photoanode and second, the photoanode should have the minimum number of scattering centers. Finally, the contained scattering center and deposited scattering layer should not allow photons to pass through.

The effects of vertical distribution of the scattering centers and scattering layers on photon distribution in the photoanode are shown in Figures 2 and 3. Based on these data, a lateral distribution of scattering centers in the photoanode should be considered to obtain the most effective photoanode structure with respect to light scattering (Figure 4). The flat and uniform distribution of scattering centers on the transparent photoanode (Figure 4a) provides a one-dimensional distribution of light within the photoanode. However, light scattering by a single scattering particle is a three-dimensional event (Figure 1), so that a three-dimensional distribution should be considered. To give an example, a dome-shaped pattern of transparent photoanodes is introduced at the interface between the flat transparent and scattering center-containing photoanode layers, as shown in Figure 4b. Introduction of the dome-shaped transparent photoanode pattern removes a portion of the scattering center as a result (Figure 4b), but the photon distribution is shifted slightly into the interface between the substrate and photoanode. The reason for this improvement should be studied further, but the dome-shaped photoanode pattern may induce a lenslike effect for the scattered light. The effect becomes clearer when the width of the dome-shaped photoanode pattern decreases and the height increases, as shown in Figure 4c, which indicates that the light distribution is shifted more toward the interface between the substrate and the photoanode. The introduction of a transparent patterned photoanode within the photoanode can modify the photon distribution, but at the same time, as shown in Figure 4, induce relatively fewer scattering centers, despite the enhanced photon distribution compared with those shown in Figure 4a. Thus, the simulation results suggest that manipulating the scattering centers and scattering layers in three dimensions provides a new way to modify the photon distribution in DSSC photoanodes for further performance improvement. Indeed, the results shown in Figure 4 have not been optimized, and many challenges remain to enhance the efficiency of photo-
anodes in DSSCs, where the distribution of scattering centers within the photoanodes, and/or the morphology of the scattering layers, could be designed in three dimensions.

Based on our simulation results on the effects of a three-dimensional distribution of scattering centers within the DSSC photoanodes, and a scattering layer on the photoanodes, the photoanode structures are designed to have an improved efficiency, as shown in Figure 5a. In this illustration, the transparent TiO₂ photoanode layer is deposited on a fluorine-doped tin oxide (FTO)-coated glass substrate, on which a 100 nm scattering center containing the photoanode and scattering layer are stacked. Between the two photoanode layers, a dome-shaped pattern of transparent photoanodes is introduced to modify the three-dimensional distribution of the scattering centers. The specific fabrication steps of photoanode are shown in Figure S3 as illustration. A cross-sectional view of the actually fabricated photoanode (Figure 5b) indicates that the design could be implemented successfully. Introduction of the patterned photoanodes can be achieved readily by repeated screen printing processes using patterned masks. As shown in Figure 5c,d, patterned transparent layers can be prepared on a flat and uniform transparent layer on which uniform scattering center-containing photoanodes and the scattering layer are deposited. The size of the pattern is changed from 0.1 to 1 mm and the thickness of the pattern can be increased up to 20 µm by increasing the number of repeated screen printings, as shown in Figure 5c,d. In these cross-sectional micrographs, repeated deposition of patterns increases the thickness without changing the pattern shape. The patterns are arrayed in a hexagonal way, and each pattern also has a hexagonal shape to fill the photoanode with a minimum area loss, as shown in Figure 5c,d.

Our novel three-dimensional scattering center design results in improved performance, according to the simulation results (Figure 6). As shown in Figure 6a, the use of our patterned transparent electrode enhances the energy conversion efficiency, mainly in terms of current density and fill factor, whereas the open circuit voltages show little change (Table S1). In terms of efficiency, according to the reciprocal of pattern width shown in Figure 6b, with a similar total transparent electrode layer thickness of 20 µm, the effect of pattern width is more obvious. When the width is fixed, the thickness of the transparent layer has little effect on performance (Figure 6c); the photovoltaic performances are listed in Table S2. At the same time, the measured diffusivity of electrons within the photoanode, shown in Figure 6d, indicates that it is insensitive to pattern size and the diffusivity of electrons has little effect on the enhanced efficiency. Diffusion of the electrons is calculated from an electrochemical impedance spectroscopy Nyquist plot (Figure S4). Thus, the enhanced efficiency of the designed electrodes would be expected according to the modified photon distribution described above, which could explain the enhanced short-circuit current density. However, further studies are required to determine the effects of the modified light distribution in the photoanode on the energy conversion performance and to identify the optimal scattering effect in or on the photoanodes of DSSCs. At this stage, the modification of light distribution is possible by manipulating the distribution of scattering centers or layers and by extending the performance of the photoanode. We have moved beyond the traditional concept of photoanodes with scattering layers, in which uniform and flat morphologies are generally assumed. Instead, we suggest that a three-dimensional photoanode design should be pursued to surmount the limitations of current DSSCs.

Figure 6. (a) Relation between current density and applied voltage (I−V curves) of DSSCs with different intermediate pattern size when the total transparent layer thickness is 20 µm and (b) the energy conversion efficiency according to width of pattern. (c) I−V curves according to total transparent thickness with a pattern width of 100 µm and (d) measured diffusivity of electron in the photoanode according to pattern width.
CONCLUSIONS

Modification of the light distribution in photoanodes of DSSCs was achieved by a three-dimensional scattering center and scattering center layer design, based on an FDTD analysis of scattering effects in the photoanode. By expanding the FDTD analysis from a single scattering center to encompass vertical and lateral distributions of multiple centers, the possible enhancement of performance through use of a transparent patterned electrode was tested in simulations and experiments. As a result, use of a 100 μm wide pattern between the transparent photoanode and scattering center-containing electrode increased the efficiency of DSSCs from 6.3 to 7.2%. These results showed that the scattering effect within a photoanode can be exploited to modify the light distribution of the photoanode, although a three-dimensional design is required for optimization and to overcome the performance limitation of current DSSCs.

EXPERIMENTAL DETAILS

Light intensity distribution simulations were performed using EM Explorer software, which was developed for finite differential time domain (FDTD) simulations. The light intensity was obtained by calculating the wave function in the forms of electric field in Maxwell equation in the time domain and then integrating in unit time. The incident light was assumed to be polarized and plane wave in harmonic form.

FDTD method solves the Maxwell equation as the optical governing equation. Maxwell equation is as follows and has been solved for E field.

$$\nabla \times (\nabla \times E) = -\mu_e \frac{\partial^2 E}{\partial t^2}$$

Incident light can be expressed as electromagnetic field by calculating the wave equation with plane wave as continuous wave.

For the boundary condition, perfectly matched layer was utilized in the z-direction and periodic boundary condition as Bloch condition was applied in the x-direction in the domain.

As the substrate for the photoanode and counter electrode, FTO (sheet resistivity 7 Ω sq⁻¹ Sigma-Aldrich) was used. The FTO glass was rinsed with acetone, ethanol, and deionized distilled water under sonication for 10 min each and dried with nitrogen gas. On the FTO glass, a blocking layer (Solaronix) was deposited by automatic screen printing (AutoMax) and sintered at 530 °C for 1 h in air. Then a transparent pattern (Solaronix) was deposited by the same process using 20 nm TiO₂ nanoparticles (Solaronix) and then sintered at 500 °C for 1 h in air. The FTO glass with deposited TiO₂ was soaked in a distilled water under sonication for 10 min each and dried with nitrogen gas. Above the transparent pattern, a mixture of small and large TiO₂ nanoparticles (CCIC) and sintered at 500 °C for 1 h in air. Above the transparent pattern, a mixture of small and large TiO₂ nanoparticles (Solaronix) was deposited as the scattering center and then dried at 70 °C in air. After the scattering center had dried, 500 nm TiO₂ nanoparticles (ENB Korea) were deposited as the scattering layer and then sintered at 500 °C for 1 h in air. The FTO glass with deposited TiO₂ was soaked in a 0.3 mM ethanol solution (Sigma-Aldrich) of N719 dye (Sigma-Aldrich) at room temperature for 20 h. The platinum paste (Solaronix) was deposited on the FTO glass by the doctor blade method, using 3 M tape as the counter electrode, and was then sintered at 450 °C. To make the cell, the TiO₂ photoanode was assembled with the counter electrode using 60 μm Surlon film (Solaronix). The liquid electrolyte was then injected into the prepared cell. The liquid electrolyte was composed of 0.6 M 1-butyl-3-methylimidazolium iodide, 0.03 M iodine, 0.1 M guanidine thiocyanate, 0.5 M 4-tert-butylpyridine, and 0.1 M lithium iodide dissolved in mixed acetonitrile and 3-methoxypropionitrile at a 2/8 volume ratio.

Field-emission scanning electron microscopy (Hitachi S4800) was performed to observe the surface and cross section of the patterned photoanode. The photovoltaic performance of the DSSCs was evaluated using a solar simulator (Sun 2000; Abet Technologies) and a 1000 W Xe source (Keithley 2400 source meter) under 1.5 AM, 1 sun conditions, with calibration done using a KG-3 filter and NREL-certified reference cell. A shading mask was applied to define the active area of 0.283 mm². We have conducted the repeatability test with three samples under same condition and variation for convincing results of DSSC. Electrochemical characterization was performed using a BioLogic SP-300 potentiostat. The impedance spectra were acquired under 0 V, 1 sun conditions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.7b01618.

AUTHOR INFORMATION

Corresponding Author
*E-mail: sicha@keri.re.kr. Tel: +82-55-280-1649.

ORCID Min Ju Yun: 0000-0003-0557-0531

Notes The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was supported by the Korea Electrotechnology Research Institute (KERI) Primary Research Program of the National Research Council of Science & Technology (NIST), funded by the Ministry of Science, ICT, and Future Planning (MSIP; no. 17-12-N0101-41).

REFERENCES

(1) O’Regan, B.; Grätzel, M. A Low-cost, High-efficiency Solar Cell based on Dye-Sensitized Colloidal TiO₂ Films. Nature 1991, 353, 737–740.
(2) Lewis, N. S. Toward Cost-Efficient Solar Energy Use. Science 2007, 315, 798–801.
(3) Grätzel, M. The Advent of Mesoscopic Injection Solar Cells. Prog. Photovoltaics: Res. Appl. 2006, 14, 429–442.
(4) Zhang, D.; Yoshida, T.; Oerkemann, T.; Furuta, K.; Minoura, H. Room-Temperature Synthesis of Porous Nanoparticulate TiO₂ Films for Flexible Dye-Sensitized Solar Cells. Adv. Funct. Mater. 2006, 16, 1228–1234.
(5) Cha, S. I.; Kim, Y.; Hwang, K. H.; Shin, Y. J.; Seo, S. H.; Lee, D. Y. Dye-Sensitized Solar Cells on Glass Paper: TCO-free Highly

DOI: 10.1021/acsomega.7b01618
Bendable Dye-Sensitized Solar Cells inspired by the Traditional Korean Door Structure. *Energy Environ. Sci.* **2012**, *5*, 6071–6075.

(6) Green, M. A.; Emery, K.; Hishikawa, Y.; Warta, W.; Dunlop, E. D.; Levi, D. H.; Ho-Baillie, A. W. Y. Solar Cell Efficiency Tables (version 49). *Prog. Photovoltaics: Res. Appl.* **2017**, *25*, 3–13.

(7) Mathew, S.; Yella, A.; Gao, P.; Humphry-Baker, R.; Curchod, B. F. E.; Ashari-Astani, N.; Tavernelli, I.; Rothlisberger, U.; Nazeeruddin, K.; Grätzel, M. Dye-Sensitized Solar Cells with 13% Efficiency Achieved through the Molecular Engineering of Porphyrim Sensitizers. *Nat. Chem.* **2014**, *6*, 242–247.

(8) Ito, S.; Miura, H.; Uchida, S.; Takata, M.; Sumioka, K.; Liska, P.; Comte, P.; Pécuy, P.; Grätzel, M. High-conversion-efficiency Organic Dye-Sensitized Solar Cells with a novel Indoline Dye. *Chem. Commun.* **2008**, *5194–5196.

(9) Wang, Z.-S.; Yamaguchi, T.; Sugihara, Y.; Arakawa, H. Significant Efficiency Improvement of the Black Dye-Sensitized Solar Cell through Protonation of TiO2 Films. *Langmuir* **2005**, *21*, 4272–4276.

(10) Yu, Y.; Wu, K.; Wang, D. Dye-Sensitized Solar Cells with Modified TiO2 Surface Chemical States: The role of Ti4+. *Appl. Phys. Lett.* **2011**, *99*, No. 192104.

(11) Wang, Z.; Kawauchi, H.; Kashima, T.; Arakawa, H. Significant Influence of TiO2 Photocathode Morphology on the Energy Conversion Efficiency of N719 Dye-Sensitized Solar Cells. *Coord. Chem. Rev.** 2004**, *248*, 1381–1389.

(12) de Freitas, J. N.; Nogueira, A. F.; Paoli, M. D. New Insights into Dye-Sensitized Solar Cells with Polymer Electrolytes. *J. Mater. Chem.* **2009**, *19*, 5279–5294.

(13) Ko, K. H.; Lee, Y. C.; Jung, Y. J. Enhanced Efficiency of Dye-Sensitized TiO2 Solar Cells (DSSC) by Doping of Metal Ions. *J. Colloid Interface Sci.* **2005**, *283*, 482–487.

(14) Baxter, J. B.; Aydi, E. S. Nanowire-based Dye-Sensitized Solar Cells. *Appl. Phys. Lett.* **2005**, *86*, No. 053114.

(15) Ito, S.; Murakami, T. N.; Comte, P.; Liska, P.; Grätzel, C.; Nazeeruddin, M. K.; Grätzel, M. Fabrication of Thin Film Dye Sensitive Solar Cells with Solar to Electric Power Conversion Efficiency over 10%. *Thin Solid Films* **2008**, *516*, 4613–4619.

(16) Li, Q.; Wu, J.; Tang, Q.; Lan, Z.; Li, P.; Lin, J.; Fan, L. Application of Microporous Polyaniiline Counter Electrode for Dye-Sensitized Solar Cells. *Electrochem. Commun.* **2008**, *10*, 1299–1302.

(17) Xue, Y.; Liu, J.; Chen, H.; Wang, R.; Li, D.; Qu, J.; Dai, L. Nitrogen-Doped Graphene Foams as Metal-Free Counter Electrodes in High-Performance Dye-Sensitized Solar Cells. *Angew. Chem., Int. Ed.* **2012**, *51*, 12124–12127.

(18) Velten, J.; Mozer, A. J.; Li, D.; Officer, D.; Wallace, G.; Baughman, B.; Zakhidov, A. Carbon Nanotube/Graphene Nanocomposite as Efficient Counter Electrodes in Dye-Sensitized Solar Cells. *Nanotechnology* **2012**, *23*, No. 085201.

(19) Yoon, C. H.; Vittal, R.; Lee, J.; Chae, W.; Kim, K. Enhanced Performance of a Dye-Sensitized Solar Cell with an Electrodeposited-Platinum Counter Electrode. *Electrochim. Acta* **2008**, *53*, 2890–2896.

(20) Ferber, J.; Luter, J. Computer Simulations of Light Scattering and Absorption in Dye-Sensitized Solar Cells. *Sol. Energy Mater. Sol. Cells* **1998**, *54*, 265–275.

(21) Zhang, Q.; Myers, D.; Lan, J.; Jenekhe, S. A.; Cao, G. Applications of Light Scattering in Dye-Sensitized Solar Cells. *Phys. Chem. Chem. Phys.* **2012**, *14*, 14982–14988.

(22) Mozaffari, N.; Mohammadi, M. R.; Carmaroudi, Z. A.; Gharavi, P. S. M. Comparative Study on Effect of Titania Morphology for Light Harvesting and Scattering of DSSCs: Mesoporous Nanoparticles, Microspheres, and Dandelion-Like Particles. *Environ. Prog. Sustainable Energy* **2016**, *35*, 1818–1826.

(23) Tan, B.; Wu, Y. Dye-Sensitized Solar Cells Based on Anatase TiO2 Nanoparticle/Nanowire Composites. *J. Phys. Chem. B* **2006**, *110*, 15932–15938.

(24) Usami, A. Theoretical study of Application of Multiple Scattering of Light to a Dye-Sensitized Nanocrystalline Photoelectrochemical Cell. *Chem. Phys. Lett.* **1997**, *277*, 105–108.