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J. Phys. Chem. C, Just Accepted Manuscript • DOI: 10.1021/jp5089146 • Publication Date (Web): 23 Oct 2014
Downloaded from http://pubs.acs.org on October 26, 2014

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Microwave Assisted Synthesis of SnO$_2$ Nanosheets Photoanodes for Dye-sensitized Solar Cells

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ABSTRACT

SnO$_2$ nanosheets were synthesized using microwave assisted hydrothermal growth and used as photoanodes for dye-sensitized solar cells (DSCs) and demonstrated much better photo-to-electrical energy conversion performance than that of SnO$_2$ synthesized with traditional hydrothermal growth, due to a significant decrease in charge diffusion distance and charge recombination. The crystallinity and microstructure of the samples were investigated by means of X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM/TEM). The specific surface area and pore size distribution were determined by means of nitrogen sorption isotherms. The interfacial charge transfer process and the charge recombination were characterized by electrochemical impedance spectrum (EIS) and intensity modulated photo-current/photo-voltage spectra (IMPS/IMVS) measurements. The DSCs assembled with SnO$_2$ nanosheets as photoanodes from microwave assisted synthesis exhibited much enhanced energy conversion efficiency, which is attributed to a higher open-circuit voltage due to less charge recombination, and a large short-circuit current density due to both large surface area and effective light scattering effect.

KEYWORDS: microwave assisted synthesis; SnO$_2$ nanosheets; dye-sensitized solar cells
INTRODUCTION

In the past decades, since the demonstration of titanium dioxide (with a band gap of 3.2 eV) nanoparticles coated with dye molecules to convert solar energy to electricity in a simple and low cost way by O’Regan and Grätzel\(^1\), synthesis of wide-bandgap oxide nanomaterials with controlled shapes and sizes has been an extensive research area for dye-sensitized solar cells (DSCs)\(^2-3\). Improving solar energy conversion efficiency at the same time reducing costs by controlling nanomaterials’ shapes, sizes, and other properties has become a significant domain\(^4\). Although a record power conversion efficiency of higher than 13% has been achieved using TiO\(_2\) nanoparticle films through the molecular engineering of porphyrin sensitizers in DSCs\(^5\), further improvement with TiO\(_2\) is difficult due to its relatively small electron mobility\(^6-7\). SnO\(_2\) as a semiconducting oxide when used as photoanode in DSCs promises many advantages: (1) Compared to the poor electron mobility of anatase TiO\(_2\) (0.1–1 cm\(^2\) V\(^{-1}\) s\(^{-1}\)), it has much higher electron mobility (100–200 cm\(^2\) V\(^{-1}\) s\(^{-1}\))\(^8-10\). (2) It has larger band gap (3.6eV) and more-negative conduction band minimum (-4.8 eV) than that of anatase TiO\(_2\) (-4.2eV), and thus can enhance light harvesting in the near-infrared spectral region when combined with small-bandgap sensitizer. (3) There are fewer oxidative holes in the valence band, contributing to long-term stability of DSCs\(^11\). In fact, SnO\(_2\) as a possible replacement of TiO\(_2\) photoanode in DSCs with various morphologies, such as nanoparticles\(^12-13\), nanofibers\(^14\), nanowires\(^15\), nanotubes\(^16\) and hollow nanospheres\(^17-20\), have been successfully synthesized and characterized. For example, Cheng et al.\(^21\) reported the synthesis of single-crystalline
SnO$_2$ nanorods with small size (15−20 nm in length and 2.5−5 nm in diameter) by hydrothermal treatment of TiCl$_4$. Wu et al.\textsuperscript{22} prepared 3D hierarchical SnO$_2$ nanostructures composed of 2D nanosheets. TiO$_2$-coated multilayered SnO$_2$ hollow microspheres had achieved 5.65% photoconversion efficiency\textsuperscript{23}.

Among various techniques used for SnO$_2$ synthesis, hydrothermal growth is one of the most common methods, which can form desired size and morphology by manipulating reactant ratio and reaction parameters\textsuperscript{24}. In contrast to the cumbersome and long-running processing nature of hydrothermal synthesis, microwave assisted synthesis offers rapid processing speed, homogeneous heating, and simple control of processing conditions, and thus has attracted much attention in last few years\textsuperscript{25}. Ding et al.\textsuperscript{26} reported synthesis TiO$_2$ nanocrystals via microwave-assisted process and demonstrated that anatase nanocrystals are highly crystalline, low in Ti$^{3+}$ defect, and free of aggregation. Hu et al.\textsuperscript{27} synthesized the linked single-crystalline ZnO rods using microwave-assisted process, demonstrating that microwave-assisted solution-phase routes can fabricate the linked ZnO rods without templates, seeds or surfactants and are suitable for large-scale production. The possibility to alter the physical and chemical properties of nanoscale materials through varying the crystal shape and size is a primary research\textsuperscript{28-30}. Chemical synthesis in a liquid phase through microwave irradiation mainly involves dipolar polarization and ionic conduction heating mechanisms\textsuperscript{25}. Using microwave assisted synthesis of SnO$_2$ is assumed to lead to different properties compared with hydrothermal synthesis.
This paper reports a microwave assisted synthesis of assembled SnO$_2$ nanosheets and their characterization and application as photoanodes in DSCs. The assembled SnO$_2$ nanosheets photoanode, with large specific surface area, effective light-scattering and an easy path for electron transport with long lifetime, demonstrated appreciably increased short-circuit photocurrent density, reduced charge recombination and consequently high power conversion efficiency. The possible mechanism was discussed about the difference between SnO$_2$ structures of microwave assisted synthesis and hydrothermal synthesis.

**EXPERIMENTAL METHODS**

**Synthesis of SnO$_2$ Nanosheets.**

Microwave assisted aqueous method: Firstly, SnCl$_2$·2H$_2$O (0.90 g, 4.0 mmol) and Na$_3$C$_6$H$_5$O$_7$·2H$_2$O (2.94 g, 10 mmol) were dissolved in distilled water (10 ml) and stirred for 5 min. Then NaOH (0.2 M, 10 ml) was added to the above solution with continuous stirring to form a homogeneous solution. The solution was transferred to a 35ml reaction tube and reactor cavity of CEM Discover microwave system. The synthesis parameters were set as: $T = 180^\circ$C, dwell time = 2h, power = 120w, and pressure = 17bars. The obtained precipitate was separated by centrifugation at 8000 rpm for 30 min and rinsed 3 times using distilled water and 3 times acetone. Finally the product was dried under vacuum at room temperature overnight. Calcination was
conducted in an electrical furnace in air at 450 °C for 4 h with a heating rate of 5 °C/min and cooled down in the static air.

**Hydrothermal method:** In a typical experiment, SnCl$_2$·2H$_2$O (4.0 mmol) and Na$_3$C$_6$H$_5$O$_7$·2H$_2$O (10 mmol) were dissolved in distilled water and stirred for 5 min. Then NaOH (0.2 M) aqueous solution was added to the above solution with continuous stirring to form a homogeneous solution. The mixture solution (10 ml) was transferred to a 25 ml Teflon-lined stainless steel autoclave and then heated in an oven at 180 °C for 12 h with a heating rate of 5 °C/min. The obtained precipitate was separated by centrifuge at 8000 rpm for 30 min and rinsed 3 times using distilled water and 3 times acetone. Finally the product was dried at room temperature overnight. Calcinations were conducted in an electrical furnace in air at 450 °C for 4 h with a heating rate of 5 °C/min cooled down in the static air.

**Preparation of SnO$_2$ Paste.** SnO$_2$ powders (0.18 g) were placed in an agate mortar, and 5.0 mL of ethanol was added dropwise into the mortar. The SnO$_2$ powders were ground for 30 min. The ground SnO$_2$ was then transferred to a solution of terpineol (0.73 g), and ethyl cellulose (0.09 g) in a 10 mL beaker under magnetic stirring. The dispersion was homogenized by means of ultrasonic and magnetical stirring overnight.

**Fabrication of DSCs.** A layer of SnO$_2$ film was prepared by the doctor blade technique. The film was sintered at 500 °C for 60 min in air to remove any organic
compounds. The resulted SnO$_2$ films were then immersed in 100 mM TiCl$_4$ aqueous solution in a closed vessel at 70 °C for 30 min. Then the films coated with TiCl$_4$ aqueous were annealed at 500 °C for 30 min before dye sensitization. The electrodes with a cell area of 0.25 cm$^2$ were immersed in a 0.25 mM N719 sensitizer dye for 18 h. The counter-electrodes were Pt coated FTO, and the electrolyte was contained I$^-$/I$^{3-}$ redox. The DSCs with TiCl$_4$ treatment and without TiCl$_4$ treatment were designed by SnO$_2$ (hydrothermal), SnO$_2$ (microwave), and SnO$_2$ (hydrothermal)-untreated, SnO$_2$ (microwave)-untreated.

**Characterization.** X-ray diffraction (XRD) measurements were conducted on an X’Pert PROS (Philips Co.) with a radiation of Cu–K$_\alpha$ ($\lambda = 1.54060$ Å). Scanning electron microscopy (SEM) measurements were undertaken by using a field emission environmental scanning electron microscope (SU8020, Hitachi Co.). Transmission electron microscope (TEM) and high resolution TEM (HRTEM) were used to study the morphology and microstructure of the materials by aJEM-2010 (JEOL) instrument. N$_2$ adsorption–desorption isotherms were recorded on ASAP2020 instrument (Micromeritics Co.), and the specific surface areas (SBET) were calculated using the BET equation. Desorption isotherm was used to determine the pore size distribution using the Barret–Joyner–Halender (BJH) method. The concentration of desorbed dye in film was calculated from UV–vis absorption spectra (UV-3600, Shi-madzu). The photovoltaic performance of DSCs was measured under a solar simulator (Oriel Sol 3A Solar Simulator, 94063A, Newport Stratford Inc.), equipped
with a 300 W xenon lamp (Newport) and a Keithley digital source meter (Keithley, 2400) controlled by Testpoint software. The irradiation intensity was calibrated to 100 mW·cm$^{-2}$ with standard reference crystalline silicon solar cell (Newport, Stratford Inc., 91150 V). The incident monochromatic photon-to-electron conversion efficiency (IPCE) plotted as a function of excitation wavelength and EIS measurements, were recorded IM6ex (Germany, Zahner Company) using light emitting diodes ($\lambda=455$ nm) driven by Expot (Germany, Zahner Company). The EIS data were fit to the equivalent circuits by using Zview software (Scribner Associates). Impedance measurements were carried out under illumination from LED. The intensity modulated photo-current/photo-voltage spectra (IMPS/IMVS) measurements were carried out with the same instrument used for EIS measurements. The LED provided both dc and ac components of the illumination.

RESULTS AND DISCUSSION

Characterization of SnO$_2$ Nanosheets.

Figure 1 shows the XRD patterns of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave), both of them have the tetragonal rutile structure with lattice constants of $a=4.738$ Å and $c=3.187$ Å (JCPDS card 41–1445). No other impurity crystal is detectable, which suggests that both microwave assisted growth and hydrothermal growth can effectively form high purity tetragonal rutile SnO$_2$ crystal.
Figure 2 are the SEM images showing (a) and (b) SnO$_2$ (hydrothermal) nanostructure, (c) and (d) SnO$_2$ (microwave) nanostructure. Both methods can form SnO$_2$ nanosheets with almost identical appearance. However, a closer look reveals the appreciable size difference of nanosheets formed by two methods. Microwave assisted synthesis resulted in a smaller SnO$_2$ nanosheets than that by hydrothermal growth. The SnO$_2$ nanosheets grown by hydrothermal method have thickness of 20–25 nm and length of 270nm, while the SnO$_2$ nanosheets grown by microwave assisted synthesis have thickness of 10nm and length of 160nm approximately. The high resolution TEM image (Figure 2b and d inset) indicates that the assembled SnO$_2$ nanosheets has a lattice spacing of 0.335 nm and 0.237nm, corresponding to the (110) lattice plane and the (200) lattice plane of tetragonal rutile SnO$_2$, respectively.

Figure 3 illustrates the nucleation and growth processes influenced by high and low ramping and cooling rates, and the growth process generally can divided into three regions. Firstly, there is no nucleation before the concentration reaches the minimum supersaturation required for nucleation (cf. Region I). Once homogeneous nucleation starts, the nucleus growth starts concurrently and very rapidly (cf. Region II). When the concentration falls below a critical nucleation concentration, nucleation stops but growth continues (cf. Region III).

Scheme 1 is the proposed schematic illustration of the formation process for the SnO$_2$ nanostructure. Nanoparticles are formed by nucleation at a different rate at the
beginning of the hydrothermal or microwave synthesis process. Microwave synthesis process can reach the reaction temperature in 3 minutes, while it needs a few hours in hydrothermal growth. The nucleation speed is affected by the concentration and temperature. Hydrothermal growth is a slow-heat process, thus the solution reaches supersaturation in a long time and the supersaturation is low leading to a wide size distribution of initial nuclei. While microwave assisted synthesis raised the solution to a desired temperature in just a few minutes, it leads to the creation of abrupt supersaturation resulting in a very high nucleation density in a very short time. During and/or immediately after the initial nucleation, the nuclei or small particles form aggregates. By reason of the difference of heating mode between hydrothermal method and microwave assisted synthesis, using microwave method can form more nuclei with more narrow size distribution due to very high heating rate and homogeneous temperature distribution compared to the hydrothermal method leading to the formation of less nuclei with broader size distribution. Small particles aggregate to form the core of the flower-like structure and grow preferentially with growth inhibition in the [0 0 1] direction, leading to the formation of large, but thin, nanosheets. Therefore, SnO$_2$ (hydrothermal) formed big sized nanosheets, while SnO$_2$ (microwave) had small length and thin thickness nanosheets.

The assembled SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) nanosheets were further characterized by means of nitrogen sorption isotherms at 77 K, and the corresponding pore size distribution is presented in Figure 4. It is found that the SnO$_2$...
(microwave) have a BET surface area of 107.5 m$^2$/g with an average Barret–Joyner–Halenda (BJH) pore diameter of 10.5 nm and a pore volume of 0.41 cm$^3$/g while the SnO$_2$(hydrothermal) have 42.6 m$^2$/g BET surface area with BJH pore diameter 10.5 nm and 0.22 cm$^3$/g pore volume.

Owing to the size and surface area differences between using hydrothermal method and microwave assisted approach to form SnO$_2$ nanostructure, it has a strong effect on the amount of dye absorption. Consequently the amount of dye absorption influences the performance of DSCs. Thus the curves of dye absorption can be seen in Figure 5 and details summarized in Table 1. The SnO$_2$ (microwave) film provides much higher dye-loading of 2.61 m$^2$g$^{-1}$ × 10$^{-7}$mol cm$^{-2}$, while that for SnO$_2$ (hydrothermal) film is only 1.62 m$^2$g$^{-1}$ × 10$^{-7}$mol cm$^{-2}$. The improved dye-loading can enhance the light harvesting efficiency, thereby the photocurrent density, and finally the cell conversion efficiency. According to the BET surface area data, SnO$_2$ (microwave) sample has 2.5 times larger surface area than SnO$_2$ (hydrothermal) sample, whereas 1.6 times more dye-loading than SnO$_2$ (hydrothermal). In theory, the value of surface area has the same effect on the amount of dye absorption. Here are two possible reasons about the differences between BET surface area data and dye-loading data: (1) Samples used in the UV–vis absorptions spectra of dyes detached from SnO$_2$ have treated with 100 mM TiCl$_4$ aqueous solution, hence TiO$_2$ can alter the surface area and influence the dye adsorption. It is different amounts of TiO$_2$ adsorbed on the surface of SnO$_2$ because large surface area favors more TiO$_2$ deposition. (2) The same volume of the SnO$_2$ pastes with different pore volume leads to different weight of two SnO$_2$ pastes.
Although SnO\textsubscript{2} (microwave) sample has 2.5 times larger surface area of 107.5 \text{m}^2/\text{g} than 42.6 \text{m}^2/\text{g} of SnO\textsubscript{2} (hydrothermal) sample, the effective exposure area ($S_{\text{BET}}$/pore volume) has small increases in fact. This is what causes the amount of dye adsorption not equal to the BET surface area. These two crucial reasons affect the radio of BET surface area and the amount of dye adsorption.

The light scattering ability of films was measured by the UV–Vis diffuse reflectance spectroscopy. As shown in Figure 6, the diffuse reflection of SnO\textsubscript{2} (microwave) film which was almost 55\% is much higher than SnO\textsubscript{2} (hydrothermal) film of 27\% at 513 nm wavelength.

Figure 1. The XRD patterns of SnO\textsubscript{2} (hydrothermal) and SnO\textsubscript{2} (microwave) powders.
Figure 2. SEM images of (a), (b) SnO$_2$ (hydrothermal) nanostructure and HRTEM images, inset, SEM images of (c), (d) SnO$_2$ (microwave) nanostructure and HRTEM images, inset. The scale bars in SEM images of (a), (c) represent 200 nm. The scale bars in SEM images of (b), (d) represent 100 nm. The scale bars in HRTEM figures represent 1 nm.
**Figure 3.** Illustration of the process of nucleation and subsequent growth where region II is nucleation zone and region III is growth zone (dash line: lower ramping rate; solid line: higher ramping rate).

![Diagram of nucleation and growth process](image)

**Scheme 1.** The schematic of the formation processes for the SnO$_2$ nanostructure, illustrating the differences between hydrothermal growth and microwave assisted synthesis.
Figure 4. Nitrogen adsorption and desorption isotherms at 77 K, and the pore size distribution (inset) of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) powders.
**Figure 5.** The UV–vis absorption spectra of dyes unloaded from SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) photoanodes.

**Table 1.** Comparison of BET surface area (S$_{BET}$), BJH pore diameter, pore volume, and the amount of dye loaded in SnO$_2$ (hydrothermal and microwave) nanostructure photoanodes.

<table>
<thead>
<tr>
<th>DSCs</th>
<th>S$_{BET}$ (m$^2$g$^{-1}$)</th>
<th>pore diameter (nm)</th>
<th>pore volume (cm$^3$/g)</th>
<th>Dye loading ($\times 10^{-7}$ mol cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$ (hydrothermal)</td>
<td>42</td>
<td>10</td>
<td>0.22</td>
<td>1.62</td>
</tr>
<tr>
<td>SnO$_2$ (microwave)</td>
<td>107</td>
<td>10</td>
<td>0.41</td>
<td>2.61</td>
</tr>
</tbody>
</table>

**Figure 6.** The curves of diffuse reflectance of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) nanostructure photoanodes without dye loading.
Characterization of Photovoltaic Properties of DSCs.

The incident photon-to-current conversion efficiency (IPCE) spectra from the cells are characterized and shown in Figure 7. The incident photo-to-current conversion efficiency clearly indicates that SnO$_2$ (microwave) with almost 40% much higher than SnO$_2$ (hydrothermal) with 30%. Despite the incident photo-to-current conversion efficiency of the SnO$_2$ (microwave) electrode has improved compared with SnO$_2$ (hydrothermal), but it is still a bit low. Because the value of IPCE is the comprehension results, related to light harvesting efficiency, electron injection efficiency, dye regeneration efficiency and charge collection efficiency.$^{34}$

In order to investigate the interfacial charge transfer process in SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) film electrodes, electrochemical impedance spectroscopy (EIS) measurements are employed in the frequency range of 0.1 Hz to 100 kHz. Figure 8 shows the Nyquist plots of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) measured at forward bias of the open-circuit voltage under 100 mW cm$^{-2}$ and the equivalent circuit, inset. From the Nyquist plots the smaller semicircle occurring at higher frequencies represents the parallel connection of charge-transfer resistance (R$_k$) and the interfacial capacitance (C$_k$) at the counter electrode/electrolyte interface. The larger one at the lower frequency region is related to the combination of charge-transfer resistance occurring at the oxide/dye/electrolyte interface (R$_{pt}$) and the chemical capacitance that stands for the change of electron density (C$_{ct}$). The semicircle of SnO$_2$ (microwave) is larger than that of SnO$_2$ (hydrothermal), probably
owing to the reduced electron transfer process in the photoanode. The larger semicircle at lower frequencies of SnO$_2$ (microwave) is much larger than that of SnO$_2$ (hydrothermal). The values of R$_{pt}$ corresponding to SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) are 29$\Omega$ and 53$\Omega$, respectively. This is taken as an evidence that SnO$_2$ (microwave) film electrodes has less charge recombination than SnO$_2$ (hydrothermal) photoanodes.

The electron transport and charge recombination of the DSCs based on SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) films were further characterized by intensity modulated photo-current spectroscopy (IMPS) and intensity modulated photo-voltage spectroscopy (IMVS). They are conducted under illumination of a LED light source ($\lambda$= 530 nm) with different light intensities from 20 Wm$^{-2}$ to 100 Wm$^{-2}$. In the Figure 9, $\tau_d$ and $\tau_r$ mean electron transit time and lifetime which is also the recombination of electrons and electrolyte. Table 2 summarizes two kinds of films results from the IMPS and IMVS plots under a light intensity 97 Wm$^{-2}$. The $\tau_d$ and $\tau_r$ can be calculated from the expression: $\tau_d = 1/2 \pi f_d$ and $\tau_r = 1/2 \pi f_r$, where $f_d$ and $f_r$ is the characteristic frequency minimum of the IMPS and IMVS imaginary component, respectively, along with the increasing light intensity. The electron diffusion coefficient ($D_n$) in SnO$_2$ films is described by the analytical expression $D_n = d^2/2.35\tau_d$ $^{35-36}$, which d is the film thickness. Combining the following equations $L_n = (D_n \times \tau_r)^{1/2}$ $^{37}$ and $\lambda_{cc} = 1 - \tau_d/\tau_r$ $^{38}$, the electron diffusion length ($L_n$) and charge-collection efficiency ($\lambda_{cc}$) can be calculated.
As shown in Figure 9, the SnO$_2$ (microwave) film shows longer lifetimes ($\tau_r$) than SnO$_2$ (hydrothermal) film. The reasons why electron lifetime has significant improved is possible that (1) SnO$_2$ of using microwave assisted synthesis method has smaller size nanosheets where can be more easily crystallized at the same sintering temperature, (2) the compact structure of SnO$_2$ using microwave assisted synthesis method can greatly reduce the electron recombination because of less reactions with iodide ions in the electrolyte. However, in theory, SnO$_2$ of using microwave assisted synthesis method to form DSC has a shorter electron lifetime than SnO$_2$ (hydrothermal) film since larger surface area would also offer more sites for charge recombination. The positive and negative effects result that SnO$_2$ (microwave) film have much longer lifetime than SnO$_2$ (hydrothermal) film, even triple times. The $\tau_d$ parameter of the SnO$_2$ (microwave) film device DSC is similar to the SnO$_2$ of hydrothermal method, indicating the transport time of two cells is parallel to each other. No matter use what kind of synthesis method to form assembled SnO$_2$ nanosheets, this will lead to many trapping sites and boundaries due to their both hierarchical structure. As a result, these trapping sites of the hierarchical structures give rise to countless trapping/detrapping events. This is the reason why the SnO$_2$ (hydrothermal) film and SnO$_2$ (microwave) film have similar transport time. $L_n$ represents the average travel distance of electrons before recombining with others. The value of $L_n$ means that the injected electron could whether transit to the external effectively. Because SnO$_2$ (microwave) film has longer electron lifetime than SnO$_2$
and higher diffusion coefficients ($D_n$), by the formula the electron diffusion lengths ($L_n$) of SnO$_2$ (microwave) film is also high. The charge collection efficiency ($\lambda_{cc}$) is the integrate result of the competition between the collection of photo-injected electrons and recombination. The calculated charge collection efficiency of SnO$_2$ (microwave) film is 90%, much more than 60% of SnO$_2$ (hydrothermal). This attributes to the much longer electron lifetime in SnO$_2$ grown using microwave assisted synthesis.

Finally, Figure 10 presents the J–V curves of DSC devices with photoanodes made of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) nanostructure. As shown in Table 3, the photoconversion efficiency of SnO$_2$ (microwave) is 3.34%, enhancing 31% from the photoconversion efficiency of SnO$_2$ (hydrothermal) with 2.55%. The main reason is the improved dye-loading, therefore the short-circuit photocurrent density has greatly improved. On the other hand, using microwave assisted synthesis method to form nanostructure can minimize the oversize SnO$_2$ flower with hydrothermal method. The small size flower can shorten the distance between semiconductor photoanode and the electrolyte, thereby form a direct path and contact.
Figure 7. IPCE spectra of DSCs with SnO$_2$ (hydrothermal), SnO$_2$ (microwave) photoanodes.
Figure 8. The Nyquist plots of electrochemical impedance spectra of SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) photoanodes.

![Nyquist plots](image)

Figure 9. Electron transport time and electron lifetime of the DSCs fabricated with SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) films as a function of the incident light intensity.

![Graph](image)

Table 2. Detailed IMPS and IMVS Parameters: Electron Transit Time ($\tau_d$), Electron Lifetime ($\tau_r$), Electron Diffusion Coefficient ($D_n$), Electron Diffusion Length ($L_n$), and Charge-Collection Efficiency ($\lambda_{cc}$) of Dye-Sensitized Solar Cells Based on SnO$_2$ (hydrothermal) and SnO$_2$ (microwave) under a light intensities 97 Wm$^{-2}$.

<table>
<thead>
<tr>
<th>DSCs</th>
<th>$\tau_d$ (ms)</th>
<th>$\tau_r$ (ms)</th>
<th>$D_n$ ($\mu$m$^2$s$^{-1}$)</th>
<th>$L_n$ (µm)</th>
<th>$\lambda_{cc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$ (microwave)</td>
<td>50.7</td>
<td>506.0</td>
<td>7553</td>
<td>61.8</td>
<td>90</td>
</tr>
<tr>
<td>SnO$_2$ (hydrothermal)</td>
<td>63.8</td>
<td>160</td>
<td>6002</td>
<td>31.0</td>
<td>60</td>
</tr>
</tbody>
</table>
Figure 10. The J–V curves of SnO$_2$ (hydrothermal), SnO$_2$ (microwave) photoanodes.

Table 3. Comparison of Short-Circuit Photocurrent Density ($J_{sc}$), Open-Circuit Photovoltage ($V_{oc}$), Fill Factor (FF), and Photoconversion Efficiency ($\eta$) for the SnO$_2$ (hydrothermal), SnO$_2$ (microwave), respectively.

<table>
<thead>
<tr>
<th>DSCs</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>$V_{oc}$ (V)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$ (microwave)</td>
<td>11.5</td>
<td>0.65</td>
<td>0.45</td>
<td>3.34</td>
</tr>
<tr>
<td>SnO$_2$ (hydrothermal)</td>
<td>8.3</td>
<td>0.63</td>
<td>0.49</td>
<td>2.55</td>
</tr>
</tbody>
</table>

CONCLUSIONS
Microwave assisted synthesis was demonstrated to produce SnO$_2$ nanosheets with substantially reduced sheet size as compared with ones synthesized by hydrothermal method SnO$_2$. Consequently, dye loading and light scattering in microwave assisted synthesized SnO$_2$ nanosheets as photoanodes in dye-sensitized solar cells were appreciably enhanced. In addition, microwave assisted synthesized SnO$_2$ nanosheets has a longer electron lifetime, and less electron recombination than hydrothermal grown SnO$_2$ electrodes; collectively, the short-circuit photocurrent density has been greatly increased.

ACKNOWLEDGEMENTS

This work was supported by the "thousands talents" program for pioneer researcher and his innovation team, China. This work was also supported by the National Science Foundation of China (51374029), Program for New Century Excellent Talents in University (NCET-13-0668) and China Postdoctoral Science Foundation (2014M550675).
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