Preparation and characterization of dye-sensitized TiO₂ nanorod solar cells

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A B S T R A C T

TiO₂ nanorods were prepared by DC reactive magnetron sputtering technique and applied to dye-sensitized solar cells (DSSCs). The length of the TiO₂ nanorods was varied from 1 μm to 6 μm. The scanning electron microscopy images show that the nanorods are perpendicular to the substrate. Both the X-ray diffraction patterns and Raman scattering results show that the nanorods have an anatase phase; no other phase has been observed. (101) and the (220) diffraction peaks have been observed for the TiO₂ nanorods. The (101) diffraction peak intensity remained constant despite the increase of nanorod length, while the intensity of the (220) diffraction peak increased almost linearly with the nanorod length. These nanorods were used as the working electrodes in DSSCs and the effect of the nanorod length on the conversion efficiency has been studied. An optimum photoelectric conversion efficiency of 4.8% has been achieved for 4 μm length nanorods.

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1. Introduction

A dye-sensitized solar cell (DSSC) is a promising device for using solar energy because of its low production cost compared to those of conventional semiconductor solar cells, and also its high light to electricity conversion efficiency [1–3]. The conventional DSSC consists of a dye-sensitized nanoporous TiO₂ coating on the transparent conducting oxide substrate as an electrode, electrolytes containing I⁻/I₃⁻ redox couple and filling the pores of the TiO₂ electrode, and a platinum counter electrode placed on the top of it. The nanoporous electrodes are generally prepared by TiO₂ nanoparticles (25 nm in diameter) by sol-gel process [4,5]. The main advantage of this nanoporous structure is its huge surface area (more than 1000 times compared to the conventional polycrystalline film), which can increase significantly the dye adsorption and improve the photoelectric conversion efficiency. However, despite its high surface area, the disordered nanoporous structure results in a short electron diffusion length because of the electron traps at the contacts between nanoparticles. The diffusion coefficient of an electron in the anatase TiO₂ nanoparticle film is several orders of magnitude lower than that in anatase TiO₂ single crystal, which limits the power conversion efficiency [6,7]. To increase the diffusion coefficient of the electrons and improve the charge transport, DSSCs using one-dimensional (1-D) structures of TiO₂ as electrodes, such as nanotubes, nanorods and nanowires, have been recently reported [8–21]. These 1-D structures will enhance the electron transport due to the features of highly decreased particle to particle contacts and elongated structure with the specified directionality [12]. Generally, these 1-D structures are made by chemical methods and a high temperature treatment is needed, which is not suitable for flexible DSSCs [13–15,17,18,20]. Magnetron sputtering technique has been considered as an adequate method for large area deposition with high uniformity at a relatively low deposition temperature. The sputtering process is easily controlled and reproduced. Generally, the TiO₂ films prepared by sputtering technique has a very compact structure, which is not suitable for DSSC applications. In our previous works, TiO₂ films with the nanorod structure have been prepared by dc reactive magnetron sputtering by adjusting the sputtering parameters and were applied as electrodes in DSSCs applications [22–26]. In this paper, the effect of the nanorod length on the structure properties of the TiO₂ films is reported. The DSSCs have been assembled using the TiO₂ films with different nanorod lengths and the effect of the nanorod length on the photoelectric properties has been studied.

2. Experimental details

The TiO₂ nanofilms were prepared on the commercial indium-tin oxide (ITO) substrates (sheet resistance of 20 Ω per square and thickness of 100 nm) by dc reactive magnetron sputtering technique using a commercial sputtering system equipped with a turbo molecular...
pumping system. A titanium metal disk (60 mm in diameter and 3 mm in thickness) with a purity of 99.99% was used as the target. After pumping down the system to $1 \times 10^{-3}$ Pa, the oxygen and argon gases (99.99% purities) were introduced into the chamber through the mass flow controllers. The oxygen partial pressure and the total sputtering pressure were kept at 0.25 Pa and 2.00 Pa, respectively. The target-substrate distance was 45 mm. The deposition time was varied to obtain the film with different nanorod lengths. The sputtering was carried out using a constant current mode. The sputtering current was kept at 0.56 A and the cathode potential was about 420 V. In order to remove the surface contaminants of the target, pre-sputtering was done for 20 min with a shutter covering the substrate. The transmittance of the films was measured using a Jasco V-550 UV–Vis spectrophotometer. The X-ray diffraction (XRD) measurements have been done using Rigaku miniflex goniometer for the 2θ ranging from 20° to 75° with a step of 0.02° using Cu Ka radiation operated at 30 kV and 15 mA as the incident radiation. The morphologies of the nanorods were studied using field emission scanning electron microscope (FE-SEM) with an operating voltage of 20 kV. Raman scattering measurements have been done using a semiconductor laser and a 532 nm laser line was used as exciting light. The laser line was focused on the sample surface in a strict 180° backscattering geometry. The TiO$_2$ films were sensitized with N719 (Ru(II)$_2$(NCS)$_2$:2TBA, where L = 2,2′-bipyridyl-4,4′-dicarboxylic acid) dye by soaking the films in an ethanolic solution of N719 dye (0.5 mM) for 24 h at room temperature. The sputtered Pt film with 100 nm thickness and 0.3 nm/s deposition rate on an FTO glass substrate was used as the counter-electrode. The electrolyte was composed of 0.1 M I$_2$, 0.1 M LiI, 0.6 M 1-hexyl-3-methylimidazolium iodide, and 0.5 M 4-tert-butylpyridine in 3-methoxypropionitrile. The photocurrent-voltage measurements were carried out with a Princeton 2273 Applied Research electrochemical system, a 500 W Xenon lamp under AM 1.5G illumination with a water filter was used. The light intensity was adjusted to 100 mW/cm$^2$. Cells with an active area of 0.15 cm$^2$ were tested.

3. Results and discussion

Fig. 1 shows the FE-SEM images of TiO$_2$ films with different nanorod lengths. The SEM images show vertically well-aligned densely-packed TiO$_2$ nanorods grown on ITO substrate. No clear variations of the structure and the dimension of these nanorods can be observed from the images with the increase of the nanorod length. Thornton suggested the zone classification by considering the final working pressure, because this growth parameter can change both the kinetic energy of the ions that arrive at the substrate and the mean free path of the particles, which allows an increase or decrease in the bombardment of the surface of the substrate, that determines the mobility of the adatoms in that surface [27]. The microstructure of the films prepared by sputtering is determined by the adatom surface mobility during the growth. At high sputtering pressure, the kinetic energy of the argon ions will be reduced due to the decrease of the mean free path and results in a very low adatom mobility. Therefore, the structure is dominated by shadowing effects that overcome limited adatom surface diffusion. The most of the sputtered fluxes are deposited on high points on the film, with little material reaching the valleys and will result in the evolution of voids surrounding the rod-shaped columns structure – nanorod array.

Fig. 2a shows the XRD patterns of the TiO$_2$ films with different nanorod lengths. All the films show an anatase phase and a preferred
The black solid circles represent the diffraction peaks from ITO. The observed in this figure. However, the intensities of these diffraction peaks do not show a very clear variation with the nanorod length. The specular transmittance of the TiO$_2$ films with different nanorod lengths are presented in Fig. 5. It can be seen that the transmittance decreases with the increase of the nanorod length. The decrease of the total energy - the sum of surface energy and deformation energy - of the system substrate-film has a minimum. The preferred orientation is determined by a configuration of minimum total energy, which results from competition between the planes with minimum deformation energy, and the planes with minimum surface energy. The average surface energies of the [110], [001], [100] and [101] crystal planes of anatase TiO$_2$ are 1.09 J/m$^2$, 0.90 J/m$^2$, 0.53 J/m$^2$ and 0.44 J/m$^2$, respectively [29]. In general, based on the Wulff construction, according to which surface energy minimization drives the optimal composition of the crystal surface, the (101) plane and the (001) plane were shown to be the most thermodynamically stable planes of anatase crystalites [30, 31], which is also in agreement with the natural minerals. However, the diffraction intensity of the (101) plane is very small in all the samples. It suggests that the preferred orientation along the [110] direction is not dominated by the minimum surface energy but by the minimum deformation energy. It has be found that, in sufficiently thin films, the surface and interface energy minimizing textures are favored, regardless of their strain or thermal history, and in thick films the deformation energy minimizing textures are favored [32]. This implies that the preferred orientation along the [110] direction is dominated by the deformation energy minimizing as the peak intensity increases with the thickness. The grain sizes along the (110) direction have been estimated from Scherrer’s formula based on the XRD data. All the TiO$_2$ films with different nanorod lengths present a similar grain size value of 24 nm. It means that the increase of the growing time does not increase the grain dimension, but increases the number of grains, and results in an increase of the nanorod length.

Fig. 4 presents the Raman spectra of TiO$_2$ films with different nanorod lengths. Five anatase TiO$_2$ Raman peaks can be observed clearly in the spectra which are in agreement with the results of XRD. The peaks at around 144, 195, and 637 cm$^{-1}$ are attributed to $E_g$ modes; the peak at 396 cm$^{-1}$ is assigned to $B_{1g}$ mode; and the peak at 513 cm$^{-1}$ consists of two modes, $A_{1g}$ + $B_{1g}$ [33]. The increase of the nanorod length does not bring any more effects on Raman spectra except for the peak intensity. The peak intensity increases gradually with the nanorod length.

The specular transmittance of the TiO$_2$ films with different nanorod lengths are presented in Fig. 5.

The intensity ratio of I(220)/I(101) has been calculated for TiO$_2$ films with different nanorod lengths and shown in Fig. 3. A linear increase of the ratio with the nanorod length can be observed. It means that the nanorod structure is favorable for the growth along the [110] direction. The thermodynamic model is generally used to explain the preferential growth direction of the films [28]. In the thermodynamic model, it has been established that the growth orientation in thin films is obtained at the thermodynamic equilibrium, which will be reached when the total energy - the sum of surface energy and deformation energy - of the system substrate-film has a minimum. The preferred orientation is determined by a configuration of minimum total energy, which results from competition between the planes with minimum deformation energy, and the planes with minimum surface energy. The average surface energies of the [110], [001], [100] and [101] crystal planes of anatase TiO$_2$ are 1.09 J/m$^2$, 0.90 J/m$^2$, 0.53 J/m$^2$ and 0.44 J/m$^2$, respectively [29]. In general, based on the Wulff construction, according to which surface energy minimization drives the optimal composition of the crystal surface, the (101) plane and the (001) plane were shown to be the most thermodynamically stable planes of anatase crystalites [30, 31], which is also in agreement with the natural minerals. However, the diffraction intensity of the (101) plane is very small in all the samples. It suggests that the preferred orientation along the [110] direction is not dominated by the minimum surface energy but by the minimum deformation energy. It has be found that, in sufficiently thin films, the surface and interface energy minimizing textures are favored, regardless of their strain or thermal history, and in thick films the deformation energy minimizing textures are favored [32]. This implies that the preferred orientation along the [110] direction is dominated by the deformation energy minimizing as the peak intensity increases with the thickness. The grain sizes along the (110) direction have been estimated from Scherrer’s formula based on the XRD data. All the TiO$_2$ films with different nanorod lengths present a similar grain size value of 24 nm. It means that the increase of the growing time does not increase the grain dimension, but increases the number of grains, and results in an increase of the nanorod length.

The specular transmittance of the TiO$_2$ films with different nanorod lengths are presented in Fig. 5. It can be seen that the transmittance decreases with the increase of the nanorod length. The decrease of the
can be calculated using the relation

\[
\alpha = \frac{\ln T}{d} 
\]

where T is the transmittance and d is the nanorod length. The optical transmittance spectra of TiO2 films with different nanorod lengths is presented in Fig. 5. The optical band gap of the TiO2 film is supposed for estimating the optical band gap \(E_g\) of the TiO2 films with different nanorod lengths using the relation [34]

\[
(\alpha h\nu)^2 \propto (h\nu - E_g) 
\]

where \(h\nu\) is the photon energy and \(\alpha\) is the absorption coefficient. The \(\alpha\) can be calculated using the relation

The optical transmittance spectra of TiO2 films with different nanorod lengths, the grain size and the distance between the (220) planes have been calculated. The grain size is about 24 nm and the distance between the (220) planes is 0.1339 nm, which is quite similar to the standard value (0.1338 nm, PDF card 21-1272) for all the samples. It means that the modification of the optical band gap in our samples cannot be explained by strain and dislocation density. In general, the amorphous phase has a larger optical band gap than the polycrystalline phase for the same material [42,43]. It can be seen from the Fig. 2 that the films with short nanorod length show a relatively weak diffraction peak intensity. This suggests that an amorphous phase coexists in the films, and results in the larger optical band gap. The percentage of the amorphous phase decreases with the increase of the nanorod length and results in a decrease of the optical band gap as shown in Fig. 6.

The DSSCs have been assembled using these TiO2 films with different nanorod lengths as the electrodes and the photocurrent density–photovoltaic performance of DSSCs is shown in Fig. 7. It can be seen that the photocurrent density increases as the nanorod length is increased from 1100 nm to 3790 nm and decreases as the nanorod length is increased further. The open-circuit voltage has a very small variation with the nanorod length. The DSSC with 6060 nm length of nanorod shows the worst fill factor. The variations of the short-circuit current density, \(J_{sc}\); open-circuit voltage, \(V_{oc}\); fill factor, FF; and conversion efficiency \(\eta\) with nanorod length are shown in Fig. 8. It can be seen that the photocurrent density governs the conversion efficiency of the DSSCs. The DSSC with a maximum photocurrent density has a maximum conversion efficiency (4.82%), which was achieved for DSSC assembled using a TiO2 film with 3790 nm nanorod length. This efficiency is higher than the work reported by Liu et al. [14] who used single-crystalline rutile TiO2 nanorods prepared by a hydrothermal method as the electrodes. The efficiency of 3% has been achieved by using 4 μm-long TiO2 nanorods. However, a conversation efficiency of 9.52% has been achieved by using 14 μm thickness TiO2 nanorod film prepared by electrospinning as reported by Lee et al. [18]. Although the conversion efficiency of this work is still not so high as some reported results using TiO2 nanorods as electrodes, it is the best one for DSSC using TiO2 nanorods prepared by magnetron sputtering method until now. The photocurrent density will be generally decided by two factors: generation and transport of the photoelectrons. The generation of the photoelectrons is related to the amount of the dye adsorbed on the TiO2 nanorods. In order to get a qualitative information on the dye adsorption, the transmittance of dye-sensitized TiO2 films with different

![Fig. 5. The optical transmittance spectra of TiO2 films with different nanorod lengths.](image)

![Fig. 6. Variation of optical band gap with the nanorod length.](image)

![Fig. 7. Comparison of the J-V characteristics of DSSCs using TiO2 films with different nanorod lengths as the electrodes.](image)
nanorod lengths have been measured as shown in Fig. 9. It can be seen from the Fig. 1 that these TiO₂ nanorods are packed very closely, the voids among the nanorods are very small, and the dye molecules can only get into the voids by the phenomenon of capillary siphon. The maximum depth which the dye molecules can reach under these experimental conditions may be limited to the certain value and the further increase of the nanorod length may have no contribution on the dye adsorption. This results in a saturation of the dye adsorption at 3790 nm length. On the other hand, further increasing the nanorod length will also increase the electron diffusion path length and will result in the increase of the possibility of the recombination of the electrons. It will decrease the photocurrent density as shown in Fig. 8.

4. Conclusions

TiO₂ films with vertically well-aligned densely-packed nanorods structure have been prepared on the ITO substrates by dc reactive magnetron sputtering. TiO₂ films with different nanorod lengths have been prepared. The variation of the nanorod length does not affect the nanorod structure. The nanorods show a preferred orientation along the [110] direction. The increase of the nanorod length enhances this orientation. The thermodynamic model has been used to explain the preferred orientation. The optical band gap decreases as the nanorod length is increased. DSSCs have been assembled using the TiO₂ films with different nanorod lengths as electrodes and the maximum conversion efficiency of 4.82% has been achieved for DSSC using a TiO₂ film with 3790 nm nanorod length.

References


Fig. 8. Variation of solar cell parameters, short circuit current density Jsc, open circuit voltage Voc, fill factor and conversion efficiency with the nanorod length.

Fig. 9. The optical transmittance spectra of TiO₂ films with different nanorod lengths after dye-adsorption. The nanorod lengths are 1100 nm, 1850 nm, 3790 nm, 4770 nm and 6060 nm for (a), (b), (c), (d) and (e) respectively.
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