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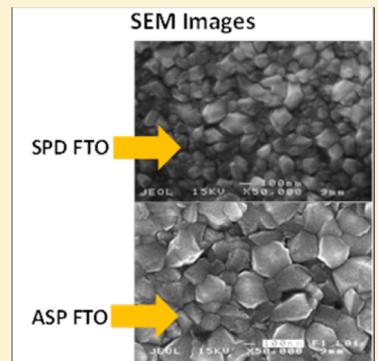
Preparation of Fluoride-Doped Tin Oxide Films on Soda–Lime Glass Substrates by Atomized Spray Pyrolysis Technique and Their Subsequent Use in Dye-Sensitized Solar Cells

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ABSTRACT: The development of a novel method for the fabrication of low-cost, transparent, conducting glass (F^- -doped SnO_2 layer on soda–lime glass, FTO) by a specially developed atomized spray pyrolysis technique using cheap soda–lime glass in place of commercially used expensive glass at a comparatively lower temperature of $450\text{ }^\circ\text{C}$ is presented. The use of these FTO plates in dye-sensitized solar cells (DSCs) will also be described. The optimum temperature of $450\text{ }^\circ\text{C}$ for the FTO layer on soda–lime glass is obtained by carrying out atomized spray pyrolysis of the precursor solution onto the soda–lime glass substrate at several different temperatures and by characterizing the materials obtained at each temperature by X-ray diffraction analysis. The FTO layers formed at $450\text{ }^\circ\text{C}$ have also been characterized by scanning electron microscopy (SEM) for morphology, grain size, and film thickness and by UV–visible transmittance spectroscopy for the optical transmission in the visible range. The electrical properties of the FTO film prepared at $450\text{ }^\circ\text{C}$ are estimated by the van der Pour method and Hall measurements. The FTO films have a uniform texture with smaller grains ($\geq 50\text{ nm}$) embedded in cages formed by larger particles ($\leq 450\text{ nm}$). The presence of large grains is important for transparent conducting glass applications. The average film thickness, estimated from the SEM images, is 560 nm . The material possesses superior electrical properties such as electronic conductivity, electron mobility, and carrier density of $1.71 \times 10^3\text{ S cm}^{-1}$, $10.89\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$, and $9.797 \times 10^{20}\text{ cm}^{-3}$, respectively, at room temperature. This low-cost technique, which uses cheap soda–lime glass for the fabrication of FTO, is better suited for commercialization. The DSCs fabricated using these FTO plates, with the cell configuration of FTO on soda–lime glass/interconnected TiO_2 nanocrystalline layer/N719 dye/ I^- , I_3^- electrolyte/mirror-type chromium-coated and lightly platinized FTO electrode, give a maximum light-to-electricity efficiency of 10.4% under AM 1.5 (100 mW cm^{-2}) illumination for a cell active area of 0.25 cm^2 .



INTRODUCTION

Transparent, conducting oxide (TCO) materials have been known for a long time, since their discovery by Badeker, who reported the electrical conductivity of the material formed by the oxidation of Cd metal deposited on the inner walls of a glow discharge tube in 1907.¹ Since then, numerous oxide materials have been exploited for TCOs, including large band gap ($E_g > 3.0\text{ eV}$) semiconducting materials such as Sb-doped SnO_2 , F-doped SnO_2 , Sn-doped In_2O_3 , Cd_2SnO_4 , $CdSnO_3$, $CdIn_2O_4$, Al-doped ZnO , Ga-doped ZnO , F-doped ZnO , and so on.² Thin films of these materials deposited on optically transparent substrates such as glass are used in many optoelectronic applications because of their high optical transparency in the visible region and high electrical conductivity. Touch-screen sensors, low-emissivity windows, liquid crystal display (LCD) devices, plasma and organic light emitting diode (OLED) displays, smart windows, and photovoltaic devices are just a few of the innumerable technological applications possible for these materials.^{2–4}

Among the numerous TCOs, those based on tin oxide are commonly used in many optoelectronic devices since the first report of Sb-doped SnO_2 as a TCO by Mochel in 1947.^{4,5} The most commonly used SnO_2 -based TCO is F-doped SnO_2 , which is commonly known as FTO. FTO has a high optical transmission in the visible range,⁶ and it also possesses high thermal and chemical stability and good electrical conductivity; in addition, the material is nontoxic and is of low-cost.^{4,7} The first report on FTO thin-layer fabrication on a glass substrate (FTO glass) was by Lytle et al. in which they used a spray pyrolysis technique to prepare FTO thin layers.⁴ TCO layers can be deposited by many other techniques, which include chemical vapor deposition (CVD),⁸ electron beam evaporation,⁹ pulsed laser deposition,¹⁰ RF magnetron sputtering,¹¹

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atomic layer epitaxy,¹² spray pyrolysis,^{6,13} and sol–gel processes.¹⁴ Among these techniques, spray pyrolysis is a simple technique, which can be used to prepare large-area films with uniform morphology. The uniformity of the film depends on the particle size distribution, and in the normal spray pyrolysis technique, a wide range of particle sizes are encountered possibly due to the aggregations of small particles. To avoid such a distribution of particle sizes, we have developed a special spray pyrolysis technique, known as the atomized spray pyrolysis (ASP), which has a component to break particle aggregates and to select only the finer particles for the depositing stream by removing the remaining coarser particles back to the feed stream. We have utilized this technique for the preparation of highly transparent, nanoporous TiO₂ nanoparticle films on FTO surfaces for applications in dye-sensitized solar cells.¹⁵ The glass substrates that are generally used in FTO glass is high-quality glass, and the high cost of this glass contributes significantly to the overall cost of FTO glass manufactured using such glass. On the other hand, soda–lime glass is very cheap, although it is not readily used to manufacture FTO glass. High-temperature processes are not favored for these glasses. This is due to the diffusion of Na⁺ ions into the SnO₂ layer, thereby changing the optical properties of SnO₂ by making it yellowish in color thus lowering the optical transparency of the material in the visible range. This happens at temperatures above 550 °C.⁷ Generally, the diffusion of Na⁺ is prevented by applying a compact hard ceramic (SiO₂, Al₂O₃, ZrO₂, or CeO₂) layer as a diffusion barrier on the soda glass substrate prior to the TCO deposition at a high temperatures (>450 °C).¹⁶ This process involves a high temperature as well as a compact layer of a hard ceramic, both of which correspond to additional costs. We report the preparation and characterization of good quality TCO films on low-cost soda–lime glasses and their applications in dye-sensitized solar cells. These glasses have more than 80% transmittance in the visible range and an electrical conductivity of $1.71 \times 10^3 \text{ S cm}^{-1}$ at room temperature. This method does not require a diffusion barrier as the Na⁺ diffusion from soda–lime glass into the FTO layer does not happen at 450 °C. The dye-sensitized solar cells fabricated using these FTO glasses with the cell configuration of FTO on soda–lime glass/interconnected TiO₂ nanoparticles/N 719 dye/I⁻, I₃⁻ electrolyte/mirror-type chromium coated and lightly platinized FTO give a maximum light-to-electricity conversion efficiency of 10.4% under AM 1.5 (100 mW cm⁻²) illumination without other additives. The use of such inexpensive FTO significantly reduces the cost of DSC fabrication.

■ EXPERIMENTAL SECTION

First, 0.901 g of SnCl₂·2H₂O (Wako Chemicals, Japan, 99%) was added to 40.0 cm³ of ethanol (Sigma-Aldrich, 95%), and the mixture was ultrasonicated for 15 min to obtain a clear solution. Then 0.24 g of saturated aqueous solution of NH₄F (Sigma-Aldrich, 99%) was added to the above solution, and the mixture was sonicated for an additional 15 min. This resulted in the formation of a translucent mixture with a haze. Concentrated HCl ($\sim 3.00 \text{ cm}^3$) was then added until the solution became clear and optically transparent.

Commercially available, soda–lime glass plates ($3 \times 5 \text{ cm}^2$) were used as substrates. The substrates were cleaned by ultrasonication in an isopropanol (Prolab, United Kingdom, 99%) bath for 10 min and were dried in a hot air flow prior to the deposition of FTO. The well-cleaned glass substrate was

placed on the surface of the hot plate of the ASP machine and heated to 150 °C. The FTO precursor solution was then sprayed on the hot glass substrate, maintained at 150 °C, using the modified ASP technique at a rate of 1.3 cm³ min⁻¹. The hot plate supporting the glass substrate was driven horizontally at a rate of 2 spray cycles per min. A discussion of the ASP technique together with a schematic representation of the setup is given in Results and Discussion. The precursor solution is drawn to the atomizing chamber with the aid of a pressurized air (0.2 MPa) flow. The solution collides on a Teflon spherule fixed in the atomizing chamber of the ASP machine and produces a flow of very fine aerosol particles, which are transferred using a Teflon hose and are impinged from a slit-type nozzle which is placed $\sim 0.5 \text{ cm}$ above the glass surface on the top surface of the glass plate. The procedure was repeated at 250, 300, 350, 400 and 450 °C, using a new glass plate in each case. The layers formed at lower temperatures are not transparent, and the best transparent layer was obtained when the deposition is carried out at 450 °C.

Titanium tetraisopropoxide (20.0 cm³) (Kanto Chemicals Co. Inc., Japan, 97%) and acetic acid (2.5 cm³, Wako Chemicals, Japan, 99.7%) were mixed with 25.0 cm³ of ethanol (Hayman, United Kingdom, 99.9%). Then steam was passed through the solution for 2 min. Rapid hydrolysis of titanium tetraisopropoxide and the expulsion of ethanol by steaming then produces a transparent solid mass consisting of TiO₂ nanoparticles. The solid mass was ground with 50.0 cm³ of deionized water in a motor for several minutes and subsequently autoclaved at 150 °C for 3 h.

To 20.0 cm³ of the above colloidal solution were added and well stirred 5.5 cm³ of acetic acid (Wako Chemicals, Japan, 99.7%), 20.0 cm³ of ethanol (Hayman, United Kingdom, 99.9%), and five drops of Triton X-100 (Sigma, U.S.). The resulting colloidal solution was ultrasonicated for 15 min, and the resulting suspension was spread on the conducting side of the FTO glass plate prepared in this work by the ASP technique at 120 °C. These TiO₂-coated FTO plates were sintered at 450 °C for 30 min in air and allowed to gradually cool to about 80 °C. The warm plates were then kept soaked in a $0.3 \times 10^{-3} \text{ M}$ solution of the *cis*-diisothiocyanato-bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II) bis(tetrabutylammonium) dye (N 719, Solaronix SA, Switzerland) in a 1:1 v/v solvent mixture of acetonitrile (Sigma-Aldrich, U.S., 99.8%) and *t*-butyl alcohol (Fluka, U.S., 99.5%) for 12 h. The plates were withdrawn from the dye solution, rinsed with acetonitrile, and dried in an air flow. These electrodes were used as the anodes (working electrodes) and mirror-type chromium coated and lightly platinized FTO plates as the cathodes (counter electrodes) in the DSCs. The presence of the reflecting chromium coat on the FTO in the counter electrode helps the reflection of the light back to the dye layer to increase the light absorption by the dye molecules. The counter electrode was placed on the working electrode, and the free space between the two electrodes was filled with the liquid electrolyte containing I⁻ and I₃⁻ redox couple to complete the DSC configuration with an active cell area of 0.25 cm². The FTO layers formed on the soda–lime glasses were characterized using X-ray diffraction (XRD; Siemens X-ray Diffractometer DS000, Cu K α_1 , $\lambda = 1.54056 \text{ \AA}$) for their crystal structure, UV-visible spectroscopy (UV1800 Shimadzu UV Spectrophotometer) for optical transmittance studies, scanning electron microscopy (SEM; JEOL 6320 F) for their surface morphology and the film thickness, and by Hall measurement

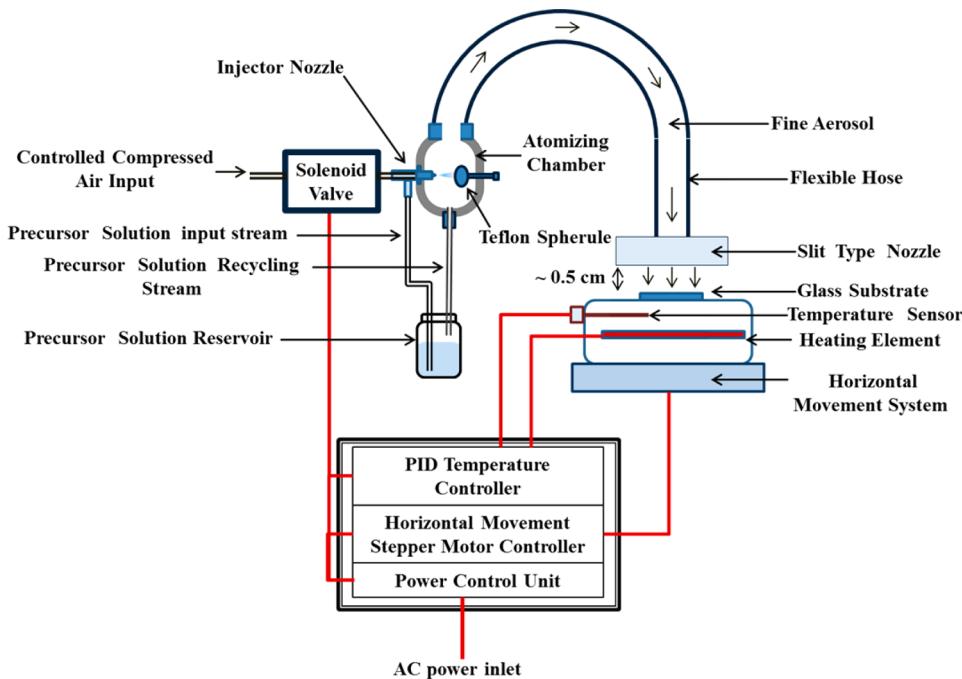


Figure 1. Schematic representation of the atomized spray pyrolysis technique developed for fabricating transparent, uniform thin films on substrate surfaces.

system (HMS-3000, ECOPiA) with van der Pauw method for the evaluation of the electrical parameters. The I – V measurements of the DSCs were obtained using a solar simulator (PECcell-L01, Japan) under AM 1.5 illumination.

RESULTS AND DISCUSSION

Atomized Spray Pyrolysis Setup. In the normal spray pyrolysis technique (SPD), the precursor solution is sprayed directly on the substrate surface and the spray head is kept about 20–30 cm above this surface. As such, the chemical species as they exist in the precursor solution, including agglomerates, if any, will be carried onto the substrate surface. This will lead to the formation of nonuniform film surfaces. This disadvantage has been overcome in the new technique of ASP in which the precursor solution is first directed to an atomizing chamber and the aerosol droplets of the precursor solution are allowed to collide with a Teflon spherule so that the aggregated particles are broken down into individual particles. As such, fine droplets of particles are deposited on the hot substrate surface. These species then undergo pyrolysis to form nucleated F/SnO_2 species on the substrate surface, which will then grow into F/SnO_2 particles. A schematic representation of the ASP technique is shown in Figure 1.

In the normal SPD technique, the nozzle is at a very large distance of about 20–30 cm above the substrate surface, whereas in the ASP method, the spray nozzle is placed just above the hot substrate surface (at about 0.5 cm). The shorter distance allows most of the droplets to be incident on the substrate surface, thus minimizing the wasting of the precursor solution; the large distance maintained in the normal SPD leads to significant wasting of the precursor solution. However, there are a few advanced versions of the SPD technique in which the precursor solution is placed in an ultrasonic bath and the ultrasonication is used to break down any aggregated particles.^{17,18} As such, the novel ASP technique is of considerable low-cost when compared to other improved

SPD techniques. In the ASP technique, the solution containing large aggregates which have not broken down into individual particles during the atomization step are recycled into the precursor solution; none of the other spray pyrolysis techniques includes such a recycling step. Obviously, the recycling of the precursor solution should minimize waste, thus contributing to further cost reduction of the overall process.

Characterization of Materials Formed at Different Temperatures by XRD Analysis. The XRD patterns of the FTO precursor solution sprayed onto soda–lime glass plates at different temperatures are shown in Figure 2. The XRD pattern of the sample prepared at 150 °C consists of peaks at 2θ values (with the planes of diffractions shown within parentheses) of 25.15° (013), 29.60° (120), 30.95° (022), 35.79° (222), and 47.02° (033). These peaks in the XRD (JCPDS card no. 84-0929) match well with those of the compound di- μ -

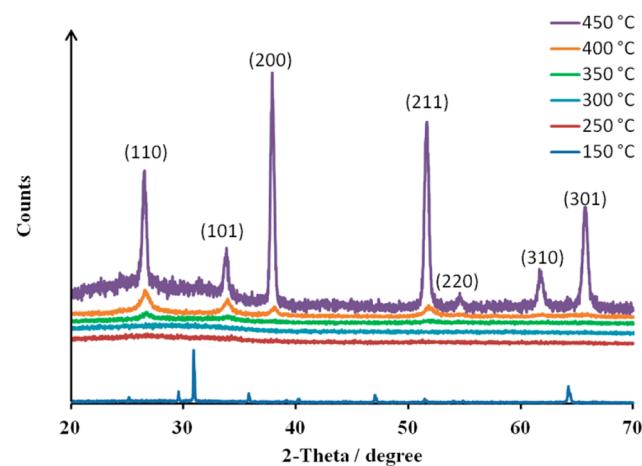


Figure 2. X-ray diffraction patterns of the films deposited on soda–lime glass using the ASP technique at different temperatures.

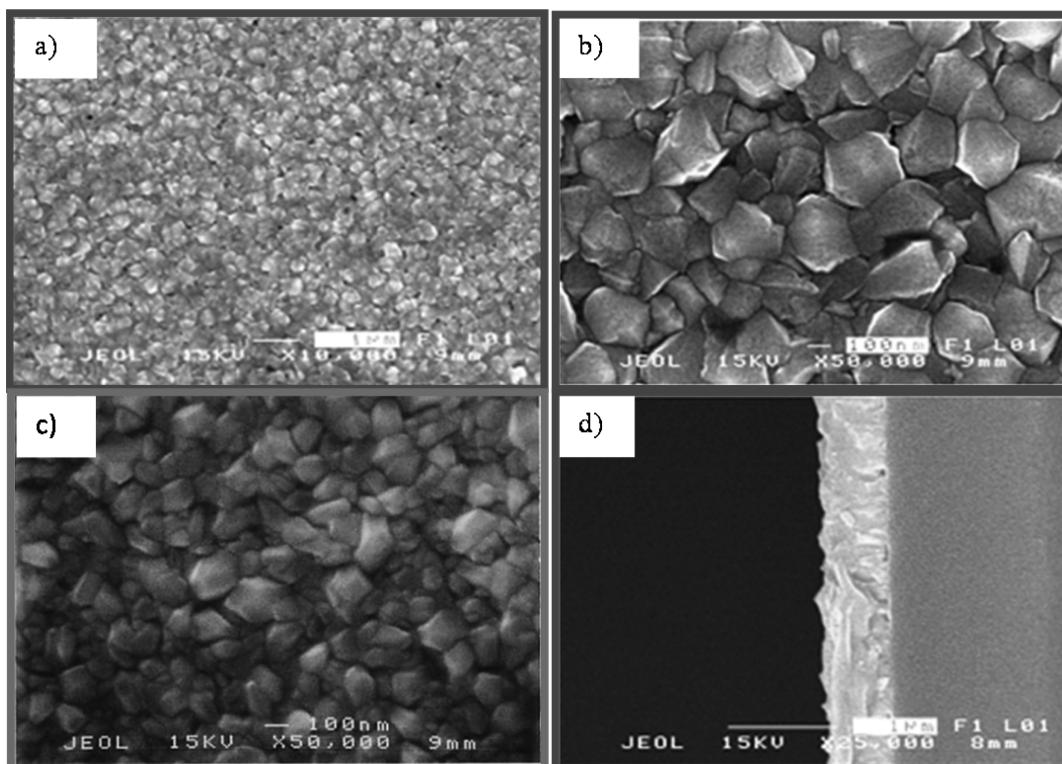


Figure 3. SEM images of the FTO deposited on soda–lime glass using the ASP technique, at 450 °C, with (a) 10 000 \times magnification and (b) 50 000 \times magnification; (d) cross-sectional SEM view of the film at a magnification of 25,000. Panel c shows an SEM image at the same magnification (50 000 \times) of an FTO layer grown using commercially available SPD equipment.

hydroxobis[fac-trichloroquinolin(IV) tetrahydrate] ($[\text{Cl}_3(\text{H}_2\text{O})\text{-Sn}(\text{OH})_2\cdot 4\text{H}_2\text{O}]$).¹⁹ This is an intermediate in the formation of SnO_2 from SnCl_2 . It is interesting to note here that $\text{SnCl}_2\cdot 2\text{H}_2\text{O}$ has undergone only partial hydrolysis and the oxidation of Sn^{2+} to Sn^{4+} followed by dimerization results in this compound. The two Sn^{4+} ions have been covalently bonded, and each of them are surrounded by three Cl, one OH, and one H_2O ligand to form a $[\text{Cl}_3(\text{H}_2\text{O})\text{Sn}(\text{OH})_2]$ structure; the compound is a tetrahydrate. This compound is highly hygroscopic and dissolves readily in adsorbed water from the ambient environment. Therefore, it is clear that a temperature of 150 °C is insufficient to form SnO_2 from SnCl_2 . The XRD patterns of the samples prepared at 250 and 300 °C do not contain any diffraction peaks suggesting that the materials formed on the glass surface at these temperatures are amorphous. It is possible, therefore, that reactants may have reacted at these temperatures, forming amorphous products such as amorphous $\text{Sn}(\text{OH})_4$ or amorphous SnO_2 . The formation of such amorphous intermediates in the synthesis of undoped SnO_2 at these temperatures has been documented.^{20,21} Therefore, a temperature of 300 °C is also insufficient to form crystalline FTO. When the deposition temperature is increased to 350 °C, the diffraction peaks corresponding to those of SnO_2 begin to appear at 2θ values of 26.6° and 33.9°, but their intensities are very low, suggesting that the formation of SnO_2 has begun at this temperature but that the main portion of the materials are amorphous intermediates. Further increase of temperature to 400 °C gives an XRD pattern similar to that at 350 °C, but intensities of the diffraction peaks of the former are 2.2 times higher than those of the latter. All the peaks are shifted by about 0.1° toward lower 2θ values. This can be explained by considering

the possibility for the creation of some oxygen vacancies due to the substitution of O^{2-} sites by F^- ions. However, this material does not have any measurable electronic conductivity, suggesting that the particles formed are not interconnected enough to have a continuous path for trapped electrons to move and that the number density of trapped electrons is very low, too. Well-developed peaks corresponding to FTO at 2θ values of 26.60° (110), 33.88° (101), 37.88° (200), 51.58° (211), 54.62° (220), 61.919° (310), and 65.78° (301) (JCPDS card no. 01-0625) can be obtained only when the deposition is carried out at 450 °C. As will be explained later, this material has all the physical properties characteristic of highly conducting FTO. Therefore, further studies of FTO layers on soda–lime glasses were carried out using the samples prepared at this temperature.

SEM Studies of FTO Layers. SEM images of the FTO layer formed on the soda–lime glass surface prepared at 450 °C are shown in Figure 3. Depicted in Figure 3a is the SEM image at 10 000 \times magnification to enable us to visualize a large surface area of the FTO layer. The crystallites are homogeneously well-arranged throughout the entire surface examined in this image. The SEM image at 50 000 \times magnification is shown in Figure 3b. The particle sizes calculated using this image show that the FTO sample is composed of particles with a few smaller (≥ 50 nm) and a majority of larger (≤ 450 nm) grain sizes, where the smaller particles lie interlocked in the middle of the cages formed by the larger particles. The SEM of the FTO layer formed by the ASP method shows an even and flat surface texture. To compare the texture and the particle size distribution of the FTO layer formed by the ASP method (Figure 3a,b) and that formed by a commercially available SPD set up (KM-150, SPD

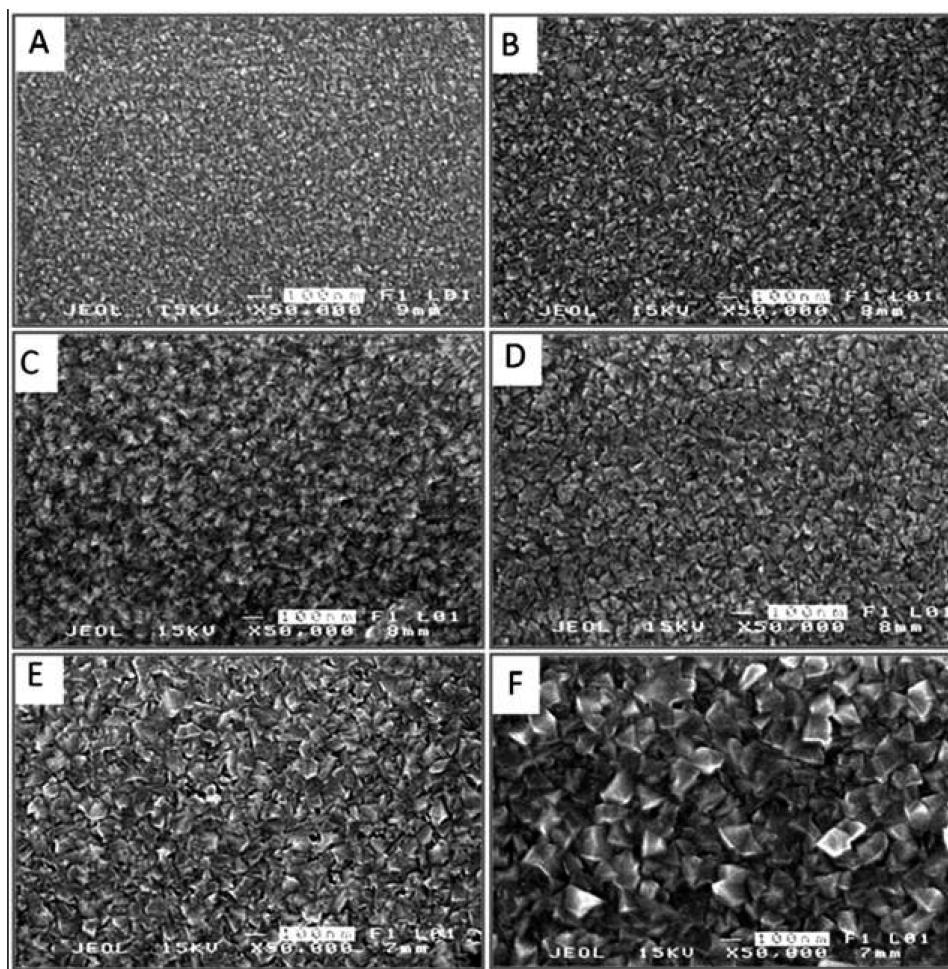


Figure 4. SEM images of FTO layers formed at different deposition times by the ASP method: (a) 1 min, (b) 2 min, (c) 3 min, (d) 4 min, (e) 5 min, and (f) 10 min deposition times.

Laboratory Co., Ltd.), an SEM of the latter at the same magnification used in Figure 3b is presented in Figure 3c. The SEM image of the commercial FTO sample, given in Figure 3c, shows that the FTO layer obtained from the commercial SPD set up is composed of particles with a range of sizes; the maximum size is ~ 250 nm, and there is an almost equal distribution of different sizes. The surface is clearly nonuniform; some agglomerated particles are clearly visible in some locations, and these agglomerated particles are concentrated in the locations where only smaller particles are present. The surface is not flat, and the particle growth in different directions is clearly visible so that the surface is composed of hills and valleys. This comparison clearly distinguishes the homogeneous texture of the FTO layer formed by the ASP method from the inhomogeneous and rough texture of the FTO layer resulting from the commercial SPD instrument.

The cross-sectional SEM image of the FTO sample (Figure 3d) is used to calculate the layer thickness, and the value obtained is around 560 nm. According to the SEM data, as we have already pointed out, our samples contain relatively larger grains and hence comparatively fewer grain boundaries than those of commercial samples.²² Hence, our samples would show electronic conductivities higher than those of commercial samples.

To understand the formation of the kind of texture of the FTO film formed by the ASP method described above, we have

systematically investigated the textures and particle size distributions of such FTO layers by depositing them for different periods of time. Figure 4 includes the SEM images of these FTO films. The results obtained are given in Table 1. It is

Table 1. Grain Sizes of the FTO Particles Formed at Different Deposition Times

deposition time (min)	grain size (nm)	
	min	max
1	10	20
2	10	50
3	30	80
4	40	100
5	40	120
10	50	150
30	50	450

clear from these data that the FTO layer formed at the very beginning is composed of very small nuclei of 10–20 nm grain sizes. As the deposition time increased, more nuclei are deposited and grow to give larger particles. This explains the formation of particles with ranges of sizes as the spray pyrolysis time is increased. The deposition for 10 min gives the particles in the size range from 50 to 150 nm where the majority of the particles are of 150 nm in size with a few smaller particles (≥ 50

nm) interlocked between the larger particles. In the original SEM image, we have shown the surface morphology of the FTO film formed at 25 min spray pyrolysis. At this time, the nuclei have grown to the highest possible size. In their growth on the surface of glass, the nuclei grow to the available spaces without growing on top of each other. This is facilitated by the smaller size of droplets incident on the substrate surface by the improved ASP method. When they grow in that manner, those smaller particles that are interlocked between large particles have no space for further growth. As such, these particles remain as smaller particles interlocked between larger particles. The SEM images of the samples prepared at longer spray pyrolysis times clearly show this behavior. The surface morphology shows only the top surfaces of the particles, which can be used to describe only the growth of particles along the surface. It is possible that the particles could grow in other dimensions, particularly in the direction normal to the surface. In that case, although the surface morphology shows a small particle, they may be large in other directions if they have grown in other directions.

Optical Properties of the FTO Thin Films Formed at 450 °C. The UV-visible transmittance spectrum recorded for the FTO sample prepared at 450 °C is shown in Figure 5. The

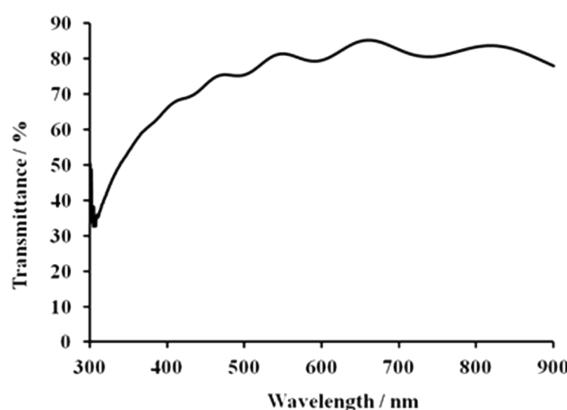


Figure 5. UV-visible transmittance spectrum of the FTO layer prepared at 450 °C using the ASP technique on soda-lime glass.

spectrum shows that the material has over 80% optical transmittance in the spectral range from 550 to 900 nm with a maximum of 85.2% at 660 nm. The transmittance in the UV range at 300 nm is 35%, and it increases gradually to about 80% in the spectral range from 300 to 550 nm. The UV-visible transmittance spectrum is composed of wave-like pattern and is characteristic of the transmittance spectrum of a thin film.

Electrical Properties of the FTO Thin Films Formed at 450 °C. The electronic conductivity σ of a semiconductor at a fixed temperature is given by $\sigma = \mu n e$, where μ is the electron mobility, n the charge carrier density, and e is the electronic charge. The electron mobility μ is related to the electronic charge e , the mean time between collisions τ , and the effective mass of electron in the semiconductor m^* by the equation $\mu = e\tau/m^*$.²³ The calculated values of the electronic conductivity, electron mobility, and the carrier density are $1.71 \times 10^3 \text{ S cm}^{-1}$, $10.89 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $9.797 \times 10^{20} \text{ cm}^3$, respectively, at room temperature. These values of electrical properties are very impressive for an FTO film on a glass surface for TCO applications, and high values of conductivity, mobility, and

carrier density reflect the quality of the FTO films prepared on ordinary soda-lime glass at a temperature as low as 450 °C.

DSC Studies. The $I-V$ curve for the DSC (active surface area of 0.25 cm^2) with optimized TiO_2 layer is shown in Figure 6. This cell generates a light-to-electricity conversion efficiency

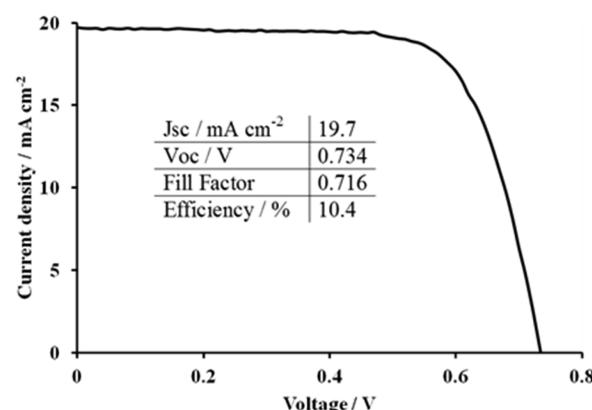


Figure 6. $I-V$ curve of the DSC (soda-lime glass/FTO/ TiO_2 nanocrystalline layer/N 719 dye/ I^- , I_3^- electrolyte/Cr-coated, lightly platinized FTO electrode) for an active area of 0.25 cm^2 of the cell, under AM 1.5 illumination.

of 10.4% under 1 Sun (100 mW cm^{-2}) illumination, with a short-circuit current density of 19.7 mA cm^{-2} , an open-circuit voltage of 734 mV , and a fill-factor of 0.716 . These values of solar cell parameters are very impressive for a DSC fabricated without materials to suppress recombination of electrons and a cocktail of dyes, scattering layers, and photonic crystals to enhance light absorption by the N 719 dye. We have fabricated 20 DSCs with different TiO_2 layer thicknesses, and all of them had fill factors exceeding 0.70, showing that the TiO_2 layer is firmly attached to the FTO layer with an Ohmic contact between the two layers thus supporting ready transfer of electrons transported along the interconnected TiO_2 particulate matrix to the FTO layer. This is further evidence for the superiority of the FTO layers deposited on ordinary soda-lime glass surfaces at a relatively low temperature.

CONCLUSIONS

Reported in this work are the fabrication of FTO layers on ordinary soda-lime glasses at a temperature lower than those generally used and the application of such FTO glasses in the fabrication of dye-sensitized solar cells. The FTO plates were fabricated at several different temperatures (from 150 to 450 °C), and each sample was characterized using XRD analysis. Good-quality FTO was obtained at only 450 °C. The FTO glasses manufactured at 450 °C have over 80% transmittance in the visible range, a homogeneous texture, and very impressive electrical properties. The DSCs fabricated using these FTO plates have over 10% efficiency, demonstrating the suitability of such low-cost FTO glasses for applications in DSCs. The use of such low-cost FTO electrodes in DSCs would enormously reduce the cost of DSC fabrication, which would help their commercialization immensely.

AUTHOR INFORMATION

Notes

The authors declare no competing financial interest.

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