Fabrication of Dye-sensitized Solar Cells Using Electrostatic Inkjet Printing

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1. Introduction

Dye-sensitized solar cells (DSSCs) have been under development since the Grätzel group reported the first example of highly efficient electrochemical photovoltaics [1-6]. DSSCs have several advantages over other types of solar cells, such as low cost fabrication, tunability with respect to the cell color, and transparency. DSSCs typically consist of a dye-adsorbed nanocrystalline titanium dioxide (TiO2) electrode, an organic electrolyte containing an iodide/triiodide redox couple, and a platinum-coated counter electrode (Figure 1). In general, the patterned TiO2 layer is important for energy conversion efficiency of DSSC devices, and printing techniques such as doctor blade and screen printing are used to develop nanocrystalline TiO2 electrodes.

In this study, we attempt to use an inkjet printing technique to develop nanocrystalline TiO2 layers.

Inkjet printing is a popular and promising technique, and thermal and piezoelectric methods are used for contemporary inkjet printers. However, it is well known that thermal and piezoelectric inkjet printers cannot eject a droplet of high-viscous liquid. TiO2 paste consists of an aqueous solution of TiO2 nano-particles, a surfactant, and polyethylene glycol, and shows very high viscosity. Recently, we developed a new inkjet technology, electrostatic-injected inkjet printing method (Figure 2) [7,8]. When the strong electric field was applied to a nozzle, small droplets were ejected by the electrostatic force. In this study, we apply this inkjet technique to develop the nanocrystalline TiO2 layers of DSSCs.

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Figure 1. Schematic illustration of the dye-sensitized solar cell.

Figure 2. Schematic illustration of the electrostatic inkjet printing method.
2. Experimental

Materials used were reagent grade or better and used as received. TiO₂ pastes were prepared as follows: TiO₂ nano-particles (NIPPON AEROSIL, AEROXIDE® TiO₂ P25), water, acetylacetone, Triton-X, and polyethyleneglycol were mixed using a planetary centrifugal mixer (THINKY, ARE-310). The resulting TiO₂ paste was printed by electric field-induced inkjet printing on fluorine-doped SnO₂-coated (FTO) glass electrodes and sintered at 450 °C for 30 min. DSSCs were prepared by a conventional procedure. The photoanodes were dipped into a 0.5 mmol l⁻¹ di-tetrabutylammonium cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)ruthenium(II) (N719 dye) solution (acetonitrile/t-butyl alcohol = 1:1) at 40 °C for several hours and treated with acetonitrile. The N719-immobilized photoanode and platinum-deposited electrode were sandwiched together using cell holders, and electrolytes were infiltrated into the resulting cells. A mixture of I₂ (0.05 mol l⁻¹), LiI (0.1 mol l⁻¹), 1,2-dimethyl-3-propylimidazolium iodide (0.6 mol l⁻¹), guanidine(0.1 mol l⁻¹), and 4-tert-butylpyridine (0.5 mol l⁻¹) was used as an electrolyte in an acetonitrile solvent. The active area of the photoanode was 0.25 cm². Photocurrent–voltage characteristics were measured using a Keithley 2400 source meter and an AM 1.5 solar simulator (Peccell PEC-L10N) equipped with a 500 W xenon lamp. Measurements were performed at room temperature under ambient conditions. Viscosity of the TiO₂ paste was measured using a viscometer (SEKONIC, VM-10A) at room temperature. The morphology of the mesoporous electrodes was characterized with a scanning electron microscope (SEM, HITACHI, S-4800).

3. Results and discussion

We have successfully fabricated a TiO₂ photoanode using an electrostatic inkjet printing technique. Very high-viscous TiO₂ paste (up to 450 mPa·s) can be ejected onto the FTO electrode. The resulting printed TiO₂ film had a very flat and smooth surface. Figure 3 shows typical photocurrent density–voltage characteristics obtained for the inkjet printed DSSC devices under AM 1.5 simulated full sunlight (100 mW cm⁻²) illumination. The resulting photovoltaic parameters of the DSSC device were short-circuit photocurrent density (Jsc) of 15.3 mA cm⁻², open-circuit photovoltage (Voc) of 0.761 V, and fill factor (ff) of 0.64. Photoenergy conversion efficiency (η) of doctor blade and inkjet printed DSSCs at different TiO₂ thickness is shown in Figure 4. The conversion efficiency increased with the film thickness of TiO₂ nanocrystalline layer and reached 6.6% and 7.5% for doctor blade and inkjet printed DSSCs, respectively. The total amount of N719 dye-sensitized molecules increased with the film thickness, which caused the photocurrent to increase. On the other hand, the total resistance of the TiO₂ film is increased with the film thickness, which caused the photocurrent to decrease. Interestingly, TiO₂ film thickness at maximum conversion efficiency for the inkjet
Figure 5. Cross-section SEM images of TiO$_2$ layers prepared by (a) doctor blade and (b) inkjet printing methods.

The inkjet printed DSSC is greater than that of the doctor blade printed DSSC. Figure 5 shows cross-section SEM images of doctor blade and inkjet printed TiO$_2$ nanocrystalline layers on FTO electrodes. The inkjet printed TiO$_2$ layer appears quite porous compared to doctor blade. To adsorb enough dye-sensitized molecules on the TiO$_2$ film, the relatively porous inkjet printed film requires a thicker nanocrystalline layer. As shown in Figure 4, the maximum conversion efficiency for the inkjet printed DSSCs is higher than that for the doctor blade printed DSSCs. One reason for this might be that the diffusion of the electrolyte (for example, I$_3^-$/$I^-$ redox couple) is easier in the porous inkjet printed nanocrystalline TiO$_2$ layer.

4. Conclusion

We successfully fabricated a TiO$_2$ photoanode using an electrostatic inkjet printing technique. The inkjet printed TiO$_2$ film was porous compared to doctor blade. Energy conversion efficiency of the inkjet printed DSSCs was 7.5% under AM 1.5 simulated full sunlight (100 mW cm$^{-2}$).

References