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A module of a TiO_2 nanocrystalline dye-sensitized solar cell with effective dimensions

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ABSTRACT

As dye-sensitized solar cells (DSSCs) have advanced to large-scale applications from lab-level research, the large-scale performance has attracted much attention. Modules of DSSCs with size up to 10 cm × 15 cm have been investigated to optimize the efficiency for effective application. Essentially, these modules have an extended structure with lab-scale works with the exception of the dimensions and methods for the series connection. The 10 cm × 10 cm modules have shown an efficiency of 6.3% without a scattering layer and over 6.6% with a scattering layer. While the fill factors of modules depend on the width of each TiO_2 unit cell, they are much less dependent on the lengths of the unit cells.

1. Introduction

Since the first successful demonstration of TiO_2 nanocrystalline dye-sensitized solar cells (DSSCs) [1], they have attracted much attention due to their low cost, steady efficiency, and relatively transparent characteristics compared to conventional inorganic thin-film solar cells [2]. In addition, they are available in a variety of bright colors whereas conventional solar cells are typically black or blue. Based on these advantages, they have a broad range of applications, including as functional windows. Although there are drawbacks associated with the use of DSSCs, such as leakage with the liquid electrolyte system at high temperatures, there continues to be intensive study towards solving these issues; thus, DSSCs can be introduced into the market. For instance, much research has involved trials to replace the liquid electrolyte with other materials such as inorganic or organic hole conductors, ionic liquids, or polymers for a better sealing of the system [3–7]. In addition, other research has focused on replacing the current solvent to a solvent with a higher boiling point. This will reduce the vapor pressure at high outdoor temperatures. Wang et al. introduced stable DSSCs that showed a high efficiency of 8% with low volatility [8]. They applied an electrolyte based on 3-methoxypropionitrile, and showed long-term stability with this electrolyte for up to 1000 h.

Although laboratory studies are well demonstrated and understood, studies of larger scale devices are limited. Many obstacles remain to be solved at the manufacturing level, including factors related to reliability, an efficient structural design for assembly, and stability-related issues. These issues are gradually being addressed. Toyoda et al. investigated possible challenges for practical outdoor uses of DSSCs with a large-scale DSSC module composed of 64 DSSC cells in a series [9]. They successfully operated the modules for nearly six months.

In the present paper, the effective dimension and structure necessary to commercialize DSSCs are demonstrated. These efforts aim at obtaining maximized efficiency from the DSSCs, which are prepared by effectively connecting individual TiO_2 unit cells in series. In essence, conditions identical to those of small lab-scale cells are utilized to fabricate a module. However, the length and width were changed in order to realize these effects.

A small number of researches have addressed optimization of a large-area DSSC array [9–11]. Krebs et al. addressed the optimum condition through a combination of three major factors: transparency control, quasi-solid-state construction, and a low-cost realization of modules [3].

2. Materials and preparation [12,13]

Anatase TiO_2 colloids were made from a sol–gel hydrolysis and autoclaving of titanium isopropoxide at 230 °C for 12 h in an acetic acid aqueous solution, as described elsewhere. The

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autoclaved colloidal solution (containing 18–25 nm size particles) was condensed into a TiO_2 concentration of 12 wt%. To control the viscosity of the solution and prevent TiO_2 film from cracking, 20 wt% polyethylene glycol (Fluka, MW 20,000) and 20 wt% polyethylene oxide (Aldrich, MW 100,000), with respect to the amount of TiO_2, were added. For scattering layer, 400 nm TiO_2 (CCIC) particles were used. The doctor blade technique with the solution was used to produce a TiO_2 film on conducting F-doped tin oxide (FTO) coated glass. For screen printing, the colloidal solution from the autoclave was treated with terpineol, lauric acid, and ethyl cellulose for a proper viscosity. The film (10 μm) was annealed at 500 °C for 30 min in air.

Silver lines were prepared as the same method for TiO_2 preparation. Silver paste was purchased from Metek, and thickness of the silver line was controlled by screen pattern thickness.

Etching was patterned by Nd:YAG pulse laser scriber (Wondar Laser). The laser wavelength, maximum output, and pulse energy are 1064 nm, 15 W, and 1 J, respectively. The resistance between two places divided by etching is over 15 MΩ.

To coat sensitizing dye on a TiO_2 nanocrystalline film, the samples were immersed in 3×10^{-4} M Ru(II)LL′(NCS)2 (L = 2,2′-bipyridyl-4,4′-dicarboxylic acid, L′ = 2,2′-bipyridyl-4,4′-ditetrabutylammonium carboxylate, Solaronix) ethanol solution overnight.

Pt coated FTO glass was prepared by spreading a few drops of 5 mM hydrogen hexachloroplatinate (IV) hydrate (Aldrich, 99.9%) 2-propanol solution on FTO glass (Pilkington, TEC 8), followed by heating at 450 °C for 30 min. After preparing two electrodes as described above, they were superposed by facing each electrode. We used surlyn film (30–40 μm) to seal the gap between electrodes for holding electrolyte.

The liquid electrolyte was composed of 0.70 M 1-vinyl-3-methyl-immidazolium iodide, 0.10 M LiI (Aldrich), 40 mM iodine (Aldrich) and 0.125 M 4-*tert*-butylpyridine (Aldrich) in 3-methoxypropionitrile (Aldrich).

The *J*–*V* curves were measured with a Keithley 2400 source meter. A 1000 W Xenon lamp (Oriel, 91193) served as a light source. The light intensity was adjusted with a reference Si cell (Fraunhofer Institute for Solar Energy System) for 1 sunlight intensity of 100 mW/cm^2.

3. Results and discussion

Fig. 1 shows the internal structure of a module of dye-sensitized solar cells prepared by connecting unit cells in a series. The series connection of each unit cells was prepared on an FTO-conducting substrate by screen printing method. As the bottom substrate is conductive through the FTO layer, it is necessary to isolate each cell by etching the FTO layer. The etching was placed directly next to silver lines that connect each isolated cell in series. If the etching for the top substrate occurs on the right side of the silver line, the etching for the bottom substrate is made on the left side of the silver line. This completes the series connection for each unit cell when they are sandwiched. The top substrate with the Pt coating, silver lines, and etching lines are assembled to complete a module. The far left line is the silver line. This silver line was completed by assembling the two silver lines of the bottom and top substrates. Fig. 2 shows the top view of the module before assembly. The thin black lines represent silver lines. The etching lines are not clear, but located right next to the silver lines. To assemble and fix two substrates, a UV-hardening polymer was applied around the silver lines on the Pt-coated substrate. Sealing was then achieved by shining UV light for 15 min after attaching the two substrates.

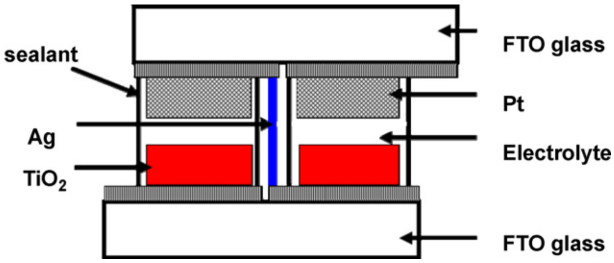

Fig. 1. The internal structure of a module of dye-sensitized solar cells prepared by connecting unit cells in a series. Connection was completed up to 10 unit cells.

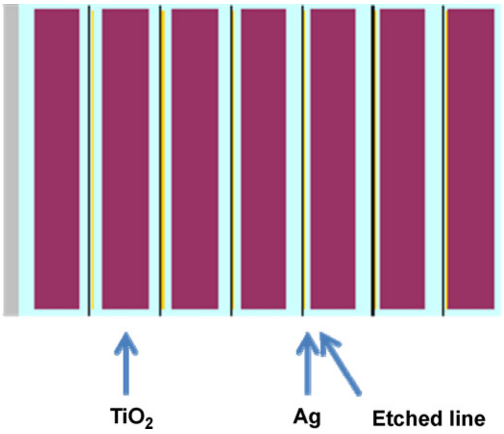

Fig. 2. The top view of the module before assembly. The thin black lines represent silver lines. The etching lines are not clear, but located right next to the silver lines.

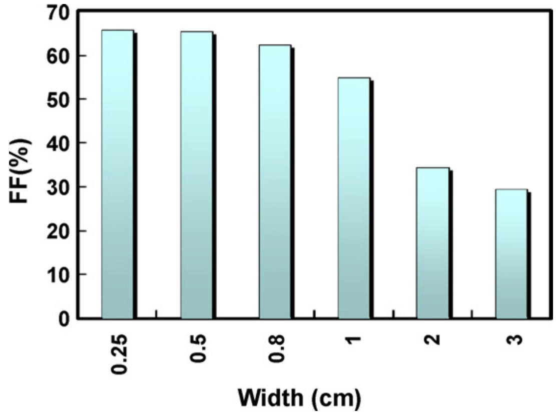

Fig. 3. The fill factor changes depending on the width of the TiO_2 individual film. The increase in the film width results in a decrease of the fill factor. The ff change is negligible until the width increases to 0.8 cm. For the experiment, the length was fixed at 10 cm. The width was changed from 0.25 cm to 3 cm.

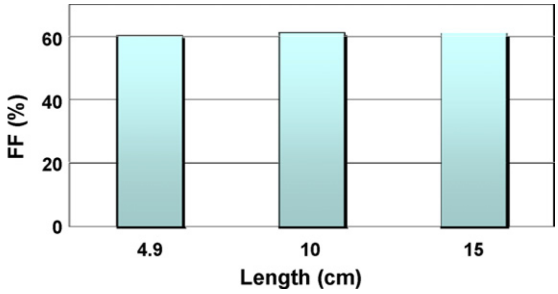

Fig. 4. The fill factor changes depending on the length of the TiO_2 individual film. The increase in the film width does not dramatically change the fill factor. The width was constant at 0.8 mm.

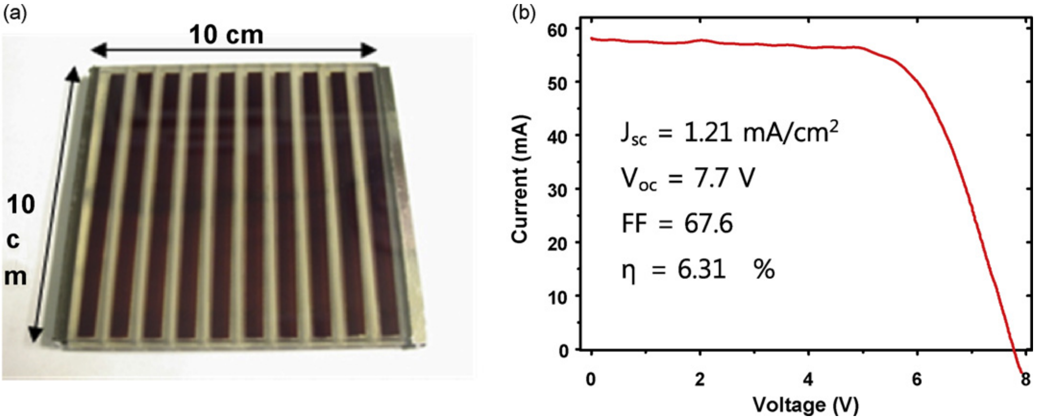

Fig. 5. A module of dimension 10 cm × 10 cm (a) and its IV characteristics (b). The active area of the module is 47.5 cm^2.

Fig. 3 shows the fill factor change depending on the width of the TiO_2 individual film. The increase in the film width results in a decrease of the fill factor. When the active area of each unit cell increases, the internal resistance increases as well. More specifically, electrons generated from the dye–TiO_2 interface find a shortcut to a silver contact to move to the next unit cell. If this path increases, electrons pass the increased resistance of the substrate and the corresponding voltage drops. Moreover, the likelihood that electrons are recombined along the substrate on their path is increased. Therefore, the fill factor drops; this is directly related to cell efficiency. According to Fig. 3, the change is not steep until the width reaches 8 mm, while it becomes more evident after 10 mm. As the maximum area without a reduction in the fill factor is expected for the highest efficiency, 8–9 mm was chosen as the optimum film width.

The length, which is not related to the distance to the anode or cathode, was varied to observe the effect on the fill factors. The width of the TiO_2 film was fixed at 5 mm and the length was varied from 50 mm to 150 mm. According to Fig. 4, the length does not affect the fill factors noticeably at a fixed width. As described above, all active electrons may gather at silver contacts. Given that the electric field is generated along this direction, a condition in which electrons are moving perpendicular to the field is not favorable. As a result, the length can be controlled to obtain a higher current flow, and the width can be controlled to obtain higher voltage with the same area substrate.

A module has been prepared with dimensions of 10 cm × 10 cm (Fig. 5(a)). The active area of the module is 47.5 cm^2. Each unit cell is 0.475 cm × 10 cm and the electrical performance of the module is illustrated in Fig. 5(b). The dimension has been decided based on the previous experimental results. The module shows 6.3% efficiency with 7.7 V as an open circuit voltage. When scattering layer (400 nm TiO_2 layer) in the cell or mirror on the backside is added, slight increase of the efficiency has been observed (6.6%).

Stability is considered as a major obstacle when modules are employed for outdoor use. As stability directly affects the total cost of a complete system, DSSCs with long-term stability are required to compete with other energy generation methods, such as a Si solar cell system. Fig. 6 shows the stability of the proposed DSSC module over time. For this test, the modules were run with a fan (the fan had been on for the period) under a continuous 1-sun condition for 63 days, which is equivalent to 1500 h. No thermal control was applied during the experiment. The local temperature of the modules averaged approximately 50 °C. The modules were stable for over 60 days. Open circuit voltage changes were within 5% of the starting values, and other value changes were in the same range. Efficiencies at the beginning stage were nearly identical to those at the ending stage.

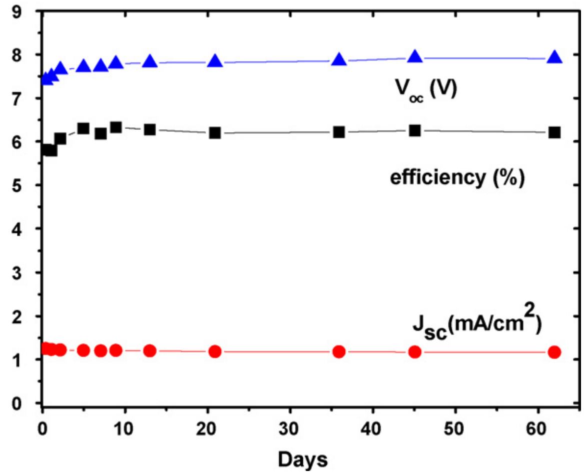

Fig. 6. The stability test for modules. 3 modules are tested, and the values were averaged.

4. Conclusion

Modules with optimum dimensions for outdoor use were successfully fabricated. The optimized structure was suggested by observing the IV characteristics according to the dimensions. While the length of each unit cell does not noticeably affect the cell efficiency, the width of the unit cells must be optimized near 8–9 mm. Modules with these dimensions showed high efficiency and stability for a period of six months.

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