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Monolithically series-interconnected transparent modules of dye-sensitized solar cells

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ABSTRACT

We have realized a new type of dye-sensitized solar cell (DSC) modules. The monolithically series interconnected structure, which is similar to the structure of amorphous silicon solar cells (SCs), was employed so that the advantages of DSCs compared to conventional silicon SCs (low costs, low energy consumption in production processes) were fully exploited. To achieve other important features of DSCs (transparency and color choice) we have developed transparent counter electrodes (CEs) composed of Pt-loaded In_2O_3:Sn nanoparticles and separators composed of SiO_2 nanoparticles to replace conventional non-transparent ones used in the modules. The performance of the new CEs is significantly improved to be close to those of conventional ones during electric generation operations. In all 85% of the maximal conversion efficiency was maintained after 2000 h of a durability test under 1 sun light soaking at 60 °C.

1. Introduction

Dye-sensitized solar cells (DSCs) have advantages of lower costs and lower energy consumption in production processes than poly-silicon solar cells (SCs) [1,2]. Transparency and color choice, which cannot be attained with other types of SCs, widen freedom of designs [3,4].

We have developed monolithically series-interconnected modules [5], which are the most promising for further reduction of costs and energy consumption in production processes. This module structure needs no second SnO_2:F (FTO)-covered glass plates used for counter electrodes (CEs) which account for more than half of total material costs and total energy consumption [6]. The fact that no complicated processes such as bonding of two glass plates or wire interconnection between single cells are involved in module production contributes to process-cost reduction and is suitable for mass-production. These modules are, however, not transparent because carbon-based black-colored CEs and rutile-based opaque separators are used.

In this study, we have developed new transparent CEs and separators which can be formed on photo-electrodes (PEs) by screen-printing, and realized transparent DSC modules of this type.

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2. Experiments

Two functions are required for CEs used in DSCs: electric conductance and catalytic activity for the reaction $I_3^- + 2\,e^- \rightarrow 3\,I^-$. To attain the former, In_2O_3:Sn (ITO) is promising because it exhibits the most excellent property as a transparent conductor. Although ITO performs as the catalyst, the activity is not enough at a high applied voltage. Pt ensures the catalytic activity, like other types of DSCs [7].

Materials used in the separators are required to be insulating and colorless. Moreover, to realize transparency in the present case, its refractive index is needed to be close to those of electrolytes used in DSCs (around 1.5 [8]). SiO_2 satisfies these requisites.

A screen-printing paste for CEs was composed of ITO nanoparticles (around 70 nm in diameter), on which Pt was chemically loaded, with ethyl-cellulose and terpineol. SiO_2 nanoparticles (30 nm) were used for separators. To maintain transparency, PEs were composed of anatase nanoparticles (20 nm) with no light-scattering large particles, and thinner than those were used to achieve high conversion efficiency. The details are described elsewhere [7].

Three-layered electrodes consisting of the PEs, new separators and new CEs were formed on glass plates covered with laser-scribed SnO_2:F layers by successive screen-printing followed by sintering. After sensitized using *cis*-bis(iso-thiocyanato)-bis(2, 2′-bipyridyl-4,4′-di-calboxylato)Ru(II)bis-tetrabutyl-ammonium (N719) and then filled with an electrolyte composed of 1, 2-dimethyl-3-propylimidazolium iodide, N-methylbenz-imidazole, iodine and γ-butyrolactone, the electrodes were back-covered with transparent damp-proof films using thermoplastic films inserted between them [5].

Fig. 1 shows a transmission electron microscope (TEM) image of the newly developed CE after the sintering. The chemically loaded Pt was found to be deposited to form islands of 2–10 nm in diameter on the ITO nanoparticles. Light absorption loss caused by the Pt islands was slight. There was no distinction in the appearance between the CEs composed of the Pt-loaded ITO and similar ITO layers with no Pt.

Detailed performance of the newly developed CEs and separators and durability under 1 sun light soaking at 60 °C were examined using monolithic single cells of a small size back-covered with glass plates (not series interconnected). Changes in current (*I*)–voltage (*V*) relationships under 1 sun irradiation, incident photon-to-current conversion efficiency (IPCE) spectra, and AC impedance spectra under 0.7 sun irradiation under an open-circuit voltage condition were monitored. A shadow mask with a 0.45 cm^2 window was used for these measurements.

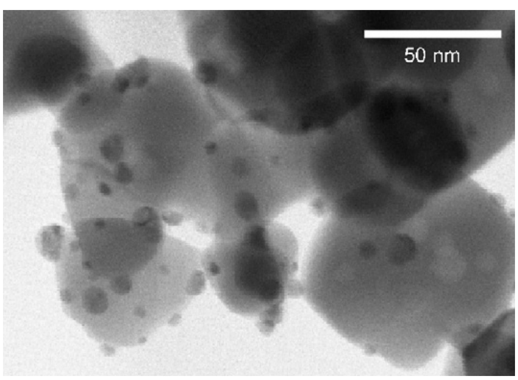

Fig. 1. TEM image of the newly developed CE composed of Pt (0.1 wt%)-loaded ITO nanoparticles. Dark spheres smaller than 10 nm are Pt islands.

3. Results and discussion

3.1. Effect of light soaking

Fig. 2 shows the change in the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), filling factor (FF) and conversion efficiency of the monolithic single cells during the light soaking. The most drastic change during the first 100 h was an improvement of FF, with a considerable increase in I_{sc}, whereas V_{oc} scarcely changed. In consequence, the conversion efficiency improved very significantly, to be close to the value of similar monolithic single cells using conventional carbon-based CEs and rutile-based separators.

Comparison of the *I*–*V* relationships before and after 96 h of the light soaking shown in Fig. 3 clearly represents the increase in I_{sc} and FF. An improvement of IPCE in the whole of the measured wavelength range shown in Fig. 4 also supports the increase in I_{sc}.

The increase in I_{sc} and IPCE often appears for similar monolithic cells using conventional CEs and separators [9] and other types of DSCs. In general, FF decreases with increasing I_{sc}, because FF is mainly determined from a voltage drop caused by a series resistance. Lower FF is usually observed at higher irradiation intensity. When I_{sc} decreases during durability tests, FF often

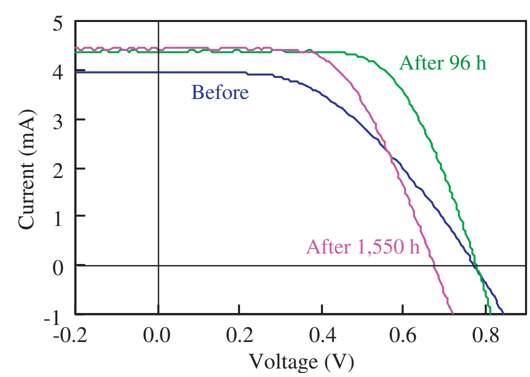

Fig. 3. Current–voltage relationships before and after the light soaking.

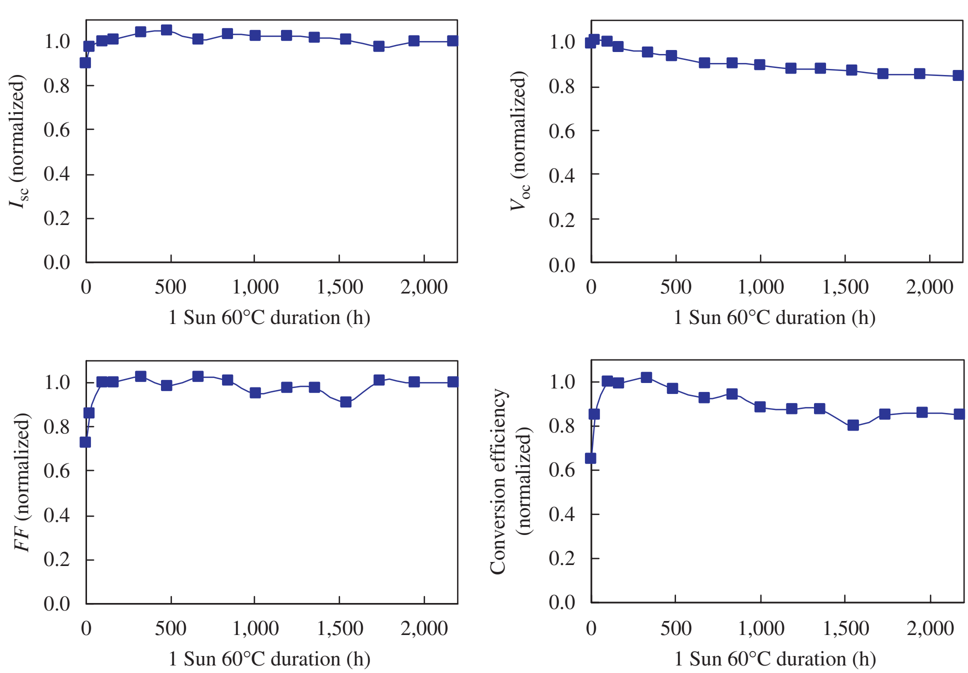

Fig. 2. Change in the performance of the monolithic single cells during the 1 sun light soaking at 60 °C.