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Photovoltaic performance degradation and recovery of the flexible dye-sensitized solar cells by bending and relaxing

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HIGHLIGHTS

► Photovoltaic performance of flexible DSCs under bending was first reported.
► Photovoltaic performance degradation and recovery mechanism was investigated.
► A modified equivalent circuit model for DSCs under bending state was proposed.

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ABSTRACT

Flexibility, as well as high efficiency, of flexible dye-sensitized solar cells (DSCs) is of significant importance to their application. In this study, the photovoltaic performance of the flexible DSCs under bending and relaxed states is investigated to understand the degradation and recovery of the photovoltaic performance. Results show that when the bending radius is larger than 8 mm, the photovoltaic parameters of the flexible DSCs maintain the same values as those in the relaxed states. However, when the bending radius is reduced to 8 mm, the photovoltaic performance is two orders of magnitude decreased. Most interestingly, when the bending DSCs are relaxed, the photovoltaic performance is found to be completely recovered. The microstructure observation shows that the direct contact between TiO_2 film and counter electrode (CE) occurred at the bending radius of 8 mm, which should be the main reason for their low photovoltaic performance in the bending state. Finally, a modified equivalent circuit model is proposed for the flexible DSCs under bending condition.

1. Introduction

Dye-sensitized solar cells (DSCs) have currently attracted widespread academic and commercial interests as a next generation photovoltaic device due to their relatively high energy conversion efficiency and low production cost [1]. Recently, there is an increasing interest in replacing rigid glass substrates with plastic substrates in considerations of light weight, flexibility and compatibility with low-cost roll-to-roll production [2–4].

Generally, high-temperature sintering (~450 °C) is required to construct the strong connection between nanoparticles and thereby the rapid electron diffusion in the photoanode for the conventional DSCs on conductive glass substrates [5]. However, the high temperature treatment cannot be employed on the conductive plastic substrates due to the low heat-resistance temperature (about 150 °C) of the plastic materials [6]. In order to improve the nanoparticle connection and mechanical stability of the TiO_2 films on such plastic substrates, other methods which can be performed at low temperature are thus expected. Over the last few years, a couple of effective methods which have been developed for plastic photoanodes include mechanical compression [7], microwave irradiation [8], hydrothermal crystallization [9], chemical sintering [10], electron-beam annealing [11], electrophoretic deposition [12] and room temperature cold spraying [13,14].

Up to now, the highest energy conversion efficiency of the assembled plastic DSCs has been up to 8.1%, which is nearly 70% of the conventional glass-based DSCs [15]. However, the flexibility, one of the most important parameters of the plastic DSCs, is rarely reported so far. Most work has been focused on improving the mechanical stability of the plastic photoanode under bending state. As an example, Jiang et al. [16] used nanowire to replace nanoparticle in the preparation of photoanode for flexible DSCs, which demonstrated a high flexibility. Li et al. [17] also improved the

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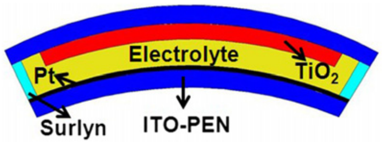

Fig. 1. The schematic of the flexible DSCs under outward bending.

flexibility by blending elastic polymer PMMA with TiO_2, though the efficiency was decreased by the presence of polymer in TiO_2 film. For all the studies until now, it should be noted that the reported photovoltaic performance of the flexible DSC was obtained for the DSCs at relaxed state. Since the flexible DSCs may work at both bending and relaxed states, the cell performance under bending state is likewise important.

In this study, TiO_2 films were fabricated on the plastic substrates by using room temperature cold spray method. The cell performance of the assembled plastic DSCs under both bending and relaxed states was investigated to examine the evolution of cell performance during bending and relaxing. The relationship between photovoltaic performance, electrochemical properties and microstructure of TiO_2 film in the flexible DSCs was studied to aim at understanding the factors which dominates the performance of flexible DSCs.

2. Experimental

2.1. Fabrication of TiO_2 film and flexible DSCs

The TiO_2 film was prepared by a home-developed room temperature cold spray system [13,14,18] using a commercial TiO_2 powder (P25, Degussa, 70% anatase and 30% rutile) with a thickness of 10 μm on ITO-PEN plastic substrate (PECF-IP, 15 Ω sq^{-1}, Peccell). The electrode was heated at 135 °C for 15 min. After cooled to 80 °C, the photoanode was immersed in an absolute ethanol solution containing 0.3 mM N719 dye (Solaronix) for 24 h, then rinsed with absolute ethanol and dried with nitrogen gas. The photoanode was then used to assemble DSCs with a plastic Pt counter electrode (CE) using a 60 μm thick Surlyn film (1702, DuPont) spacer. The electrolyte solution was introduced into the cell through four holes predrilled on the back of the plastic CE, then the holes were sealed up using an UV resin (ThreeBond). The electrolyte solution was composed of 0.6 M DMPII (Institute of Plasma Physics), 0.05 M I_2 (Aldrich), 0.1 M LiI (Aldrich), and 0.5 M 4-*tert*-butylpyridine (Acros) in dehydrated acetonitrile (Aldrich).

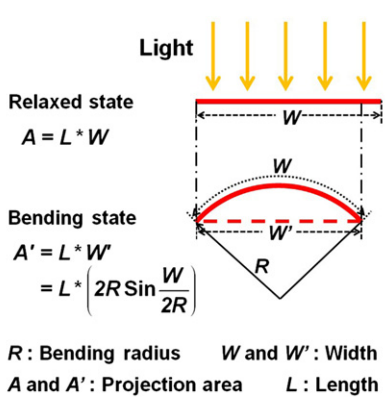

Fig. 2. The schematic of the calculation of the projection area of the photoanode under bending state and relaxed state.

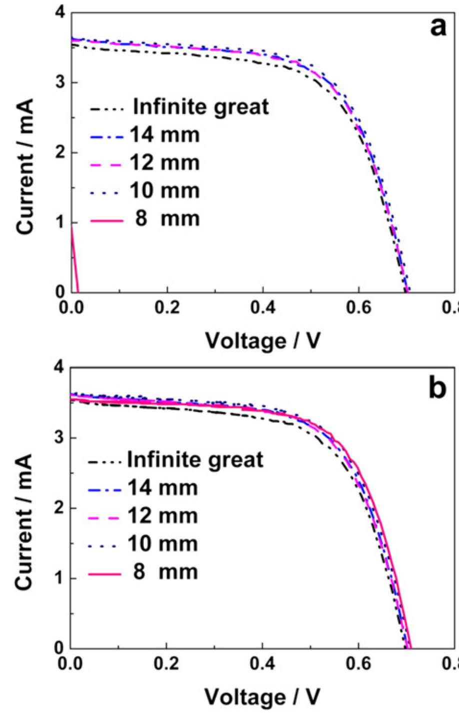

Fig. 3. The I–V curves of the flexible DSCs measured under bending state (a) and relaxed state (b) with different bending radii.

2.2. Characterization of flexible DSCs

The bending test was carried out by a home-developed flexible solar cell bending tester, by which the bending conditions, including bending direction, bending radius and bending times, were accurately controlled. Fig. 1 shows the schematic of the flexible DSC under outward bending. The photovoltaic performance of

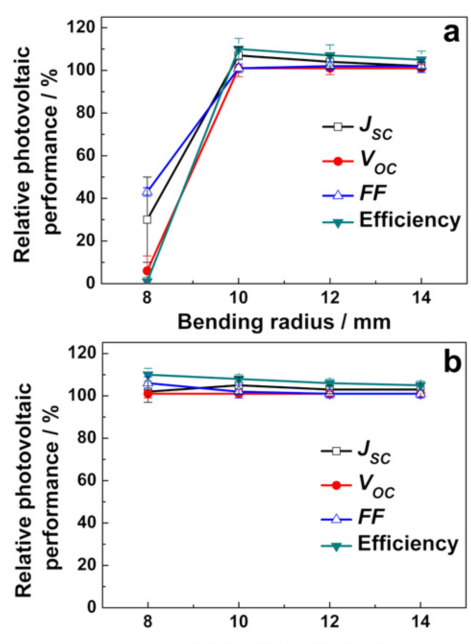

Fig. 4. Relative photovoltaic parameters of the flexible DSCs measured under bending state (a) and relaxed state (b) as a function of bending radius.