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Compact and high-power dye-sensitized solar system integrated with low-cost solar-concentrating polymer lens

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ABSTRACT

A dye-sensitized solar cell (DSSC) is integrated monolithically with a polymer lens to demonstrate a compact, low-cost and high-power solar energy harvesting system. The proposed polymer lens is composed of a plano-convex lens for concentrating light and a supporting layer for controlling the distance between the lens and DSSC according to its thickness. A single-step polymer replication process with a glass-based lens mold makes it possible to fabricate the polymer lens in a simple and reproducible manner. The power conversion performance of the polymer lens-integrated dye-sensitized (PLD) solar system is optimized by simply controlling the height of the supporting layer. The maximum output power of DSSC is improved by ~50.2% after monolithically integrating with the polymer lens with a 3-mm-thick supporting layer. Finally, the PLD solar system is packaged with a self-cleanable polymer film to protect the lens from the environment and to make the system robust to contamination. Through a simple self-cleaning test, it is found that the PLD system can recover ~95.2% of its original output power.

1. Introduction

A high price-to-performance ratio is one of the most crucial factors that should be considered in developing solar energy harvesters. To achieve this, many efforts have been made over the past decades to enhance the light-to-power conversion performance of dye-sensitized solar cells (DSSCs), which have superior cost-effectiveness in manufacturing compared to other semiconductor cells [1–8]. To date, extensive research on the development of new materials and architectures for DSSCs has resulted in steady enhancement of output power [9–16]. In addition to the approaches, a multifunctional luminescent fluoropolymer coating has been introduced to improve power conversion efficiency and long-term stability of DSSCs [17,18]. Optical lenses can also be integrated with DSSCs to enhance the output power by directly concentrating the sunlight onto the photoactive electrodes [19–21]. This approach makes it possible to increase the output power of DSSCs efficiently and is potentially feasible for further enhancement of the output power when combined with material and structural strategies [21]. However, lens-integrated solar systems inevitably become bulky and complicated because several mechanical parts must also be integrated into the system to physically support the lens, as well as to control the focal length by adjusting the distance between the lens and solar cell. Furthermore, the use of expensive glass-based lenses significantly increases the overall manufacturing cost of integrated solar systems. These issues critically hinder applications in various fields that require high-power, compact, and cost-effective solar energy harvesters.

This work demonstrates a low-cost polymer lens that can potentially be employed as a solar-concentrating device for developing a compact and high-power dye-sensitized solar system. The polymer lens was simply prepared from a glass-based lens mold through a standard polydimethylsiloxane (PDMS) replication process. The lens was monolithically integrated with a DSSC by bonding it onto the top surface. There are several advantages of the polymer lens-integrated dye-sensitized (PLD) solar system compared to conventional lens-integrated solar systems as follows. First, the overall manufacturing cost can be dramatically reduced by replacing expensive glass-based lenses with low-cost polymer ones while maintaining fair optical performance due to the high transparency of PDMS. Second, compact architecture is highly achievable because the polymer lens can be monolithically integrated with a DSSC, and the system performance can be easily controlled by adjusting the thickness of the lens structure without any mechanical parts. Finally, the polymer

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lens is very robust to dust contamination, physical damages, and self-cleanable because the lens is fully packaged with a self-cleanable PDMS film.

2. Experimental details

2.1. Fabrication of polymer lens and self-cleanable film

The polymer lens and self-cleanable film were simply prepared by a PDMS replication process. For fabrication of the polymer lens, a plano-concave glass-based lens (Edmund Optics) was placed inside a plastic container and used as a mold. The diameter, edge thickness, and center thickness of the plano-concave lens are 8.4, 3.63, and 2.25 mm, respectively. A PDMS prepolymer (Sylgard 184 A, Dow Corning) mixed with a curing agent (Sylgard 184 B, Dow Corning) at a weight ratio of 10:1 was poured into the container, followed by thermal curing in a convection oven at 70 °C for 1 h. The polymer lens was finally prepared by peeling it off from the mold.

For fabrication of the self-cleanable PDMS film, a ~70-μm-thick photoresist layer (PR, JSR THB-151N; JSR Micro) with square holes was periodically patterned on a silicon substrate using a photolithographic process. The PDMS/curing-agent mixture (at a weight ratio of 10:1) was then spin-coated onto the mold substrate at 500 rpm for 30 s and then cured at 70 °C for 1 h. The micro-pillar-arrayed PDMS film was carefully peeled off from the mold substrate and coated conformally with a thin fluorocarbon (FC) layer using a chemical vapor deposition (CVD) method to decrease the surface energy.

2.2. Fabrication of DSSC

DSSCs were fabricated using guidelines from previous studies [20,22]. Commercially available TiO_2 nanoparticles (NPs) were purchased (P25, Degussa, Sigma-Aldrich) and used without further treatment. The photoactive electrode was a screen-printed TiO_2 thin film on fluorine-doped tin oxide (FTO) glass (SnO_2:F, 7 Ω/sq, Pilkington) with a photoactive area of 0.6×0.6 cm^2. Briefly, TiO_2 NPs-based paste was prepared for screen printing process by mixing 6 g of TiO_2 NPs, 15 g of ethanol, 1 mL of acetic acid (CH_3COOH), and 20 g of terpineol in a vial and sonicating for 1 h. A solution of 3 g of ethylcellulose dissolved in 27 g of ethanol was also prepared and mixed with the TiO_2 NP-dispersed solution and sonicated for 30 min.

The resulting TiO_2 paste was screen-printed on FTO glass pre-treated with a solution of 0.247 mL of $TiOCl_2$ and 20 mL of deionized water to enhance the adhesion between the TiO_2 thin films. The TiO_2 thin film on the FTO glass was then sintered in an electric furnace at 500 °C for 30 min and immersed in anhydrous ethanol containing 0.3 mM of Ru-dye $(Bu_4N)_2[Ru(Hdcbpy)_2\text{-}(NCS)_2]$ (N719 dye, Solaronix) for 24 h at room temperature for adsorption of dye molecules on the surface of the TiO_2 thin films. The dye-soaked TiO_2 photoactive electrode was then rinsed with ethanol and dried in a convection oven at 80 °C for 10 min.

Pt-coated FTO glass was prepared by ion sputtering (E1010, Hitachi) at 2.5 kV and used as a counter electrode. Both the dye-adsorbed TiO_2 photoactive electrode and the Pt-coated counter electrode were assembled into a sandwich-type structure with a 60-μm-thick hot-melt polymer film (Surlyn, DuPont) as a spacer. The internal space between the electrodes was then filled with an iodide-based liquid electrolyte (AN-50, Solaronix).

2.3. Characterization

Isotropic and cross-sectional images of the fabricated polymer lens and PLD solar system were obtained with a digital camera. The 2D surface and cross-sectional profiles of the glass-based lens mold and polymer lens were observed using a laser interferometer (NV-1000, Nanosystem). The detailed surface morphology of the fabricated polymer lens was measured using an atomic force microscope (AFM; NX10, Park Systems) in non-contact mode. The surface geometry of the fabricated self-cleanable film was observed using an optical microscope (BX60M, Olympus) and laser interferometer.

The surface wetting property of the self-cleanable film was evaluated by characterizing the static contact angle (SCA) and contact angle hysteresis (CAH) using a contact angle meter (DSA 20E, KRÜSS) equipped with a CCD camera module. The optical property of the self-cleanable film was characterized by measuring the optical transmittance at wavelengths ranging from 400 to 800 nm with an air baseline using UV–visible spectroscopy (S310, SCINCO).

The power conversion performance of the PLD solar system was evaluated by characterizing the output power density under AM 1.5 simulated illumination with an intensity of 100 mW/cm^2 using a commercially available solar simulator (PEC-L11, Peccell Technologies). The output power density (P_o) can be defined as $P_o = J_{sc} \times V_{oc} \times FF$, where J_{sc}, V_{oc}, and FF are short-circuit current density, open-circuit voltage, and fill factor, respectively. The measurements were performed on at least three systems for each model with different heights of the supporting PDMS.

The self-cleaning performance of the PLD solar system was characterized by comparing the output power densities of the system in initial, contaminated, and cleaned states. The PLD solar system was contaminated by randomly scattering alumina microparticles onto the top surface and cleaned by introducing several water droplets onto the contaminated surface at an inclination of ~10°.

3. Results and discussion

Fig. 1(a) shows a schematic illustration of the PLD solar system under light illumination. The polymer lens consists of the plano-convex lens and supporting PDMS parts and it is monolithically integrated onto the top surface of the DSSC. The lens part plays a role in concentrating the incident light and focusing it onto the photoactive electrode of the DSSC. The light-to-electricity power output of the PLD solar system can be optimized easily by controlling the height (h_s) of the supporting PDMS. This is because the circular area of light focused onto the photoactive electrode is determined by the distance between the lens and the DSSC.

Fig. 1(b) shows the calculated radius of the focused light area (R_l) as a function of h_s of up to 5 mm. The details for the calculation are described in Fig. S1 in the Supporting Information (SI). When increasing h_s, the circular area of focused light becomes smaller due to a gradual decrease of R_l. This indicates that the incident light is more densely concentrated onto the photoactive electrode with a fixed area of 0.6×0.6 cm^2 (an increase in the utilization rate of the focused light area), while the utilization rate of the photoactive electrode is accordingly decreased, as shown in the inset of Fig. 1(b) and Fig. S2 in the SI. This also suggests that the power conversion performance of the PLD solar system can be systematically optimized by controlling h_s to mediate between the two contradictory factors (the utilization rates of the focused light area and the photoactive electrode). To estimate effect of h_s on the power conversion performance of the PLD solar system, the calculated utilization rates of the focused light area and photoactive electrode were averaged while varying the weighting of the two factors, as shown in Fig. S3 in the SI. Assuming that the two factors predominantly determine the performance of the PLD solar system, h_s can be designed to achieve maximum performance at the highest average utilization rates, as shown in Table S1.