



Application of micro-porous polycarbonate membranes in dye-sensitized solar cells: Cell performance and long-term stability

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ABSTRACT

This research investigates the cell performance and long-term stability of dye-sensitized solar cells (DSSCs) containing micro-porous polycarbonate (PC) film as the frame work material to stabilize the electrolyte solution. The track-etched PC film has cylindrical pore geometry, which is beneficial for ion transport in the electrolyte trapped inside the PC film. The photovoltaic efficiency of the DSSC with 0.2- μm PC membrane is $5.75 \pm 0.73\%$ under irradiation of 100 mW cm^{-2} , which is slightly lower than that ($6.34 \pm 0.44\%$) of cells without PC film. The differences in fill factor and open-circuit voltage between the DSSCs with and without PC film are not statistically significant. The long-term cell performance is carried out at continuous illumination of 100 mW cm^{-2} (1 sun) and in darkness at 60°C for up to 1000 h. There is no significant efficiency difference between the cells with and without PC film in light soaking (4.33% vs. 4.52%) for 960 h. In darkness, however, the cells with PC film demonstrate much higher efficiency (at 2.37%) than cells without PC (0.85%) after 1000 h. The improved long-term efficiency data and the higher percentage of working cells confirm the superior lifetime and performance using the micro-porous PC film.

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1. Introduction

Solar cells are considered one of the most important renewable power sources. Although silicon-based solar cells are in mass production at present [1], the high-vacuum process results in high manufacturing costs [2]. Dye-sensitized solar cells (DSSCs) can be fabricated without using a vacuum environment and possess a substantial price advantage. A typical DSSC consists of conductive transparent glass with nano-structured TiO_2 , light harvesting dye, I^-/I_3^- electrolyte in acetonitrile, with Pt-coated conductive glass as the counter electrode [3]. The overall solar conversion efficiency is a product of the short-circuit current density (J_{sc}), the open-circuit voltage (V_{oc}), and the fill factor (FF). Therefore, the only way to improve the conversion efficiency is to increase J_{sc} , V_{oc} , and the FF. The FF is the ratio of maximum power from the solar cell to the product of V_{oc} and J_{sc} . Accordingly, a FF value closer to 1.0 is ideal [4]. The V_{oc} is the difference between the Nernstian potential of the solution and the semiconductor's quasi-Fermi level. At open-circuit voltage, the electron injection and recombination/interception rates are equal, and their values determine

the steady-state electron concentration in the semiconductor and therefore its quasi-Fermi level [5]. The short-circuit current is the maximum current a solar cell produces under illumination of a standard light source and corresponds to the current flow through the solar cell under an external load of zero (equivalent to a loop short circuit). The conversion efficiency of solar cells is affected mainly by its structural characteristics, material properties, working cell temperature and environmental changes.

The challenges in DSSCs lay in the lifetime issue. The liquid electrolytes suffer from liquid volatilization and leakage, thus reducing the cell efficiency and eventually shortening the lifetime. Research on improving electrolyte stability includes the use of solid or gel electrolyte [6–8], replacing volatile solvents with ionic liquids [9,10], and the incorporation of polymeric films into DSSCs [11–14]. The ion diffusivity is slower in the solid electrolytes and ionic liquids. Therefore, micro-porous films as the frame work material seem to have potential use due to their solvent retention capability from the capillary force exerted between the porous support and liquid. Kim et al. fabricated a DSSC with a gel polymer electrolyte and showed a more stable photovoltaic performance than with a DSSC assembled with a liquid electrolyte [11]. Zhang et al. prepared quasi-solid-state DSSCs by adding poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) in polycarbonate (PC)-based gel polymer electrolyte and liquid organic electrolyte [12]. Wei et al. prepared PVDF-HFP/polyethylene glycol (PEG)/polyethylene glycol dimethacrylate

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(PEGDMA) cross-linked film for DSSC. Their micro-porous structure was controlled by the solvent evaporation behavior [13]. Park et al. prepared a flat film with a honey-comb like morphology directly on a dye-adsorbed TiO₂ electrode via a simple dip coating process. The liquid electrolyte was trapped in the pores of the honey-comb like structure, which could retard liquid electrolyte leakage [15].

This work investigates DSSC efficiency by incorporating micro-porous polycarbonate (PC) film and studies the long-term cell performance using this micro-porous support. The photocurrent density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and light-to-electrical energy conversion efficiency were recorded for as-prepared and aged cells after illumination or being kept in darkness for 1000 h. The PC film incorporation effect on the cell performance was examined.

2. Experimental

2.1. Materials

Ruthenium 535 bis-TBA (N719) dye was purchased from Dyesol Ltd., Queanbeyan, Australia. Acetonitrile, iodine (purity of 99.9%), and isopropyl alcohol (IPA) were obtained from J.T. Baker (Phillipsburg, NJ, USA). tert-Butanol (purity of 99%), lithium iodide hydrate (99.99%), 4-tert-butylpyridine (TBP, 99%) and hydrogen hexachloroplatinate(IV) hydrate (H₂PtCl₆) were from Aldrich (St. Louis, MO, USA). 1-Methyl-3-propylimidazolium iodide (PMII) was synthesized by the Photovoltaics Technology Center at the Industrial Technology Research Institute (ITRI). Fluorine-doped tin oxide (FTO) conductive glass was from NSG America Inc., Somerset, NJ, USA. Hot melt sealing foil (SX1170-60) was from Solaronix SA (Aubonne, Switzerland). Colloidal silver liquid was purchased from Ted Pella Inc. (Redding, CA, USA). The polycarbonate (PC) film with nominal pore size of 0.2 μm was obtained from Whatman Ltd., London, United Kingdom.

2.2. PC characterization

The PC film thickness was measured using a thickness gauge (Elcometer® 345, Elcometer Inc., Manchester, England). The mean pore size was measured using capillary flow porometry (Porous Materials, Inc., Ithaca, NY, USA). Galwick (surface tension of 15.9 dynes cm⁻¹) was used as the wetting solvent and the PC sample was analyzed using the wet up/dry down mode. The film surface morphology was examined using a field-emission scanning electron microscopy (model S-4800, Hitachi Ltd., Tokyo, Japan) after being coated with gold. The 20 kV voltage and 75 μA current were used during operation. The micrograms were determined using image analyzer software for porosity determination. The thermal stability was measured on a thermal analyzer/mass spectrometer (model STA 409CD/QUADSTAR-422, Netzsch, Selb, Germany). The sample was heated at a rate of 10 °C min⁻¹ under a helium atmosphere. The PC film was immersed in electrolyte solution for 24 h and measured for the resistance using a potentiostat/galvanostat (model PGSTAT3, Autolab, ECO Chemie B.V., Utrecht, Netherlands). The thickness of the swollen film was measured to determine the dimensional stability. The chemical compatibility was performed by weighing the PC film before and after immersion in acetonitrile solvent.

2.3. DSSC preparation

Fluorine-doped tin oxide (FTO) conductive glass of 2.5 cm × 1.5 cm was used as the electrode substrate. The photocatalytic TiO₂ paste was synthesized by ITRI and screen-printed onto the FTO substrate with an active area of 0.28 cm². The electrode was heated to 400 °C for 20 min. The electrode was then

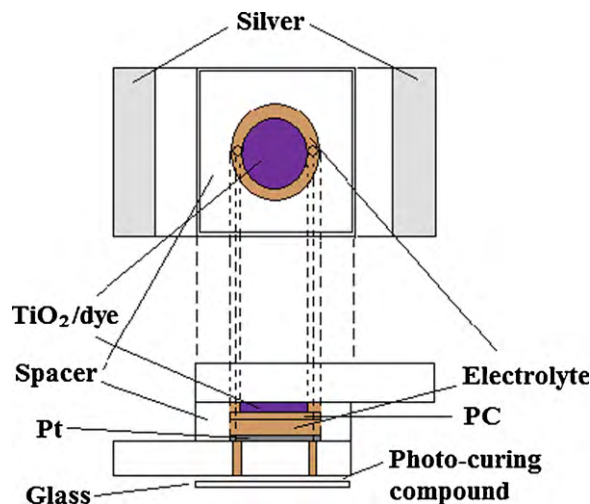


Fig. 1. Top and cross-sectional illustrations of DSSC.

immersed in a N719 dye solution of 5×10^{-4} M in acetonitrile/tert-butanol (1:1, v/v) solution at 60 °C for 3 h to adsorb the dye molecules. The electrode was rinsed with acetone to remove excess dye solution and dried at 80 °C for 2 min.

The counter electrode was prepared by screen-printing with H₂PtCl₆ (0.015 M in IPA) on another FTO glass, on which two holes were drilled. The counter electrode was annealed at 400 °C for 20 min and gradually cooled to room temperature for 10 min. After the TiO₂ electrode, the PC film and the counter electrode were carefully aligned. Hot melt sealing foil was then used to seal the DSSC using hot-pressing at 130 °C for 40 s under 65 kN cm⁻² pressure. The electrolyte solution (0.6 M PMII/0.05 M I₂/0.1 M LiI/0.5 M TBP in acetonitrile) was injected into one hole on the counter electrode. The holes were sealed using ultraviolet (UV) light after photo-curing compound was placed in the holes and covered by a slide glass. Fig. 1 shows the top and cross-sectional views of the assembled DSSC. Colloidal silver liquid was coated on the FTO glasses of the electrode and counter electrode and air dried for conducting currents to a potentiostat.

2.4. Cell performance test

The assembled DSSC performance was measured under illumination of 100 mW cm⁻² (Xenon lamp power supply, model YSS-100A, Yamashita Denso Corporation, Tokyo, Japan) at room temperature for as-prepared and aged cells. The cells were aged in three conditions for long-term stability tests: in darkness at room temperature, in light soaking of 100 mW cm⁻² (1 sun, AM 1.5) at 60 °C and 5% relative humidity (using xenon weather-ometer, model Ci3000, SDL Atlas, Rock Hill, SC, USA), in darkness at 60 °C and 5% relative humidity (in climate chamber, model KBF240, Binder, Tuttlingen, Germany).

The cell was first activated for 20 min and the photocurrent and voltage were recorded. The efficiency (η) was determined using Eq. (1):

$$\eta (\%) = \frac{V_{oc} \times J_{sc} \times FF}{P_{in}} \times 100 \quad (1)$$

where V_{oc} is open-circuit voltage (the maximum voltage value), J_{sc} is short-circuit current density (the maximum current density value), FF is fill factor and is determined using Eq. (2), P_{in} is incident light power.

$$FF = \frac{J_{max} V_{max}}{J_{sc} V_{oc}} \quad (2)$$

where J_{\max} and V_{\max} are the current and voltage values which give the maximum product value. For accelerating aging tests, the DSSCs were double-sealed with UV-curing compound and stored at 60 °C.

3. Results and discussion

3.1. PC membrane characterization

The PC film was examined for the pore size and morphology using SEM. The micrograms in Fig. 2 showed the circular pore morphology of this track-etched film. The pores were perpendicular to the film surface and exhibited cylindrical geometry. This non-tortuous path is beneficial for ion transport. The mean pore size was estimated to be 0.208 μm , not significantly different from the nominal pore size (0.2 μm) specified by the vendor. The porosity (the void fraction per unit volume of the porous film) was evaluated from the total pore cross-sectional area within the scanned area and the value was 10.51%. The film thickness was measured as 5.62 μm using the thickness gauge.

The PC film was heated up to 182 °C in a thermal analyzer and no significant weight loss (less than 2%) was found (Fig. 3). The mass spectrometer installed on the outlet stream did not detect any signals resulting from the fragments. The data showed insignificant degradation of the PC matrix, opposite to the phenomena observed by Grünwald and Tributsch [16]. This PC material was thermally stable for the DSSC application.

The PC film was immersed in acetonitrile solvent. The swollen film thickness was increased to 5.92 μm . The thickness increase

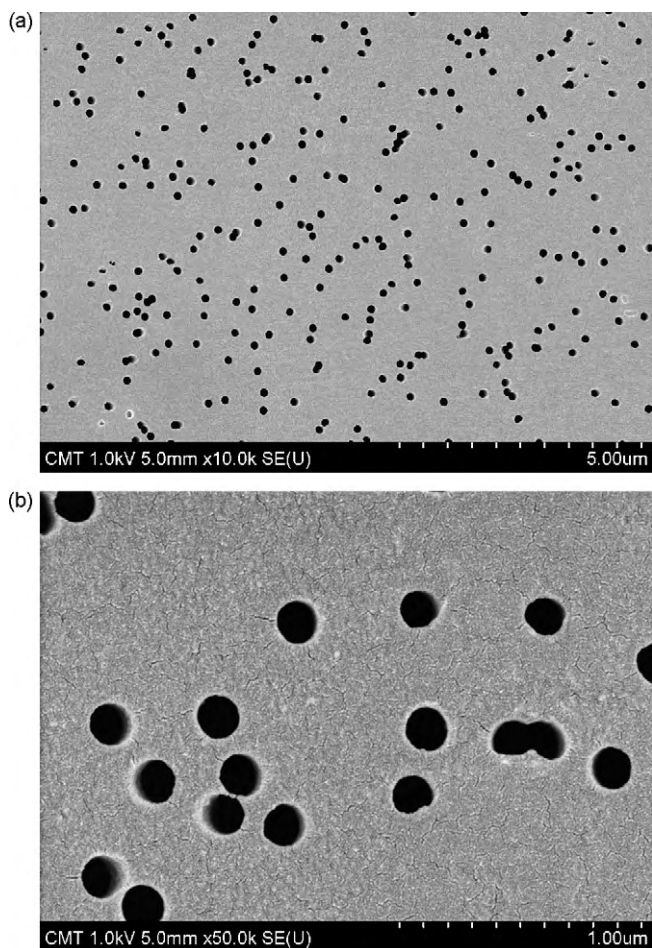


Fig. 2. Scanning electron micrograms of PC micro-porous film with nominal pore size of 0.2 μm at (a) 10,000 and (b) 50,000 magnification.

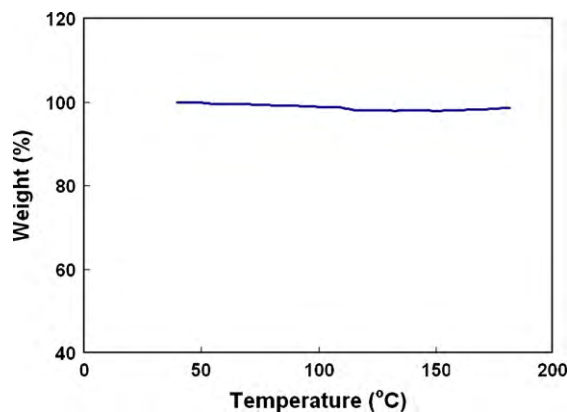


Fig. 3. Weight loss of polycarbonate film upon heating.

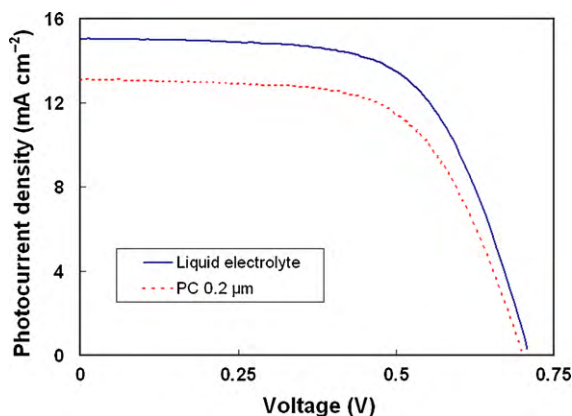


Fig. 4. Photocurrent density–voltage curves for dye-sensitized solar cells, assembled with liquid electrolyte and with PC micro-porous support, under illumination of 100 mW cm^{-2} (1 sun).

after swelling was only 5.34%. This dimensional change was insignificant and expected to have negligible impact on the cell sealing. The dry weights before and after the immersion were the same (0.0011 g), indicating that the PC did not dissolve in the acetonitrile solvent. The PC film filled with electrolyte solution was measured for the resistance and the value of 0.625 Ω was obtained.

3.2. Cell performance of as-prepared DSSCs

Typical photocurrent density–voltage curves for solar cells based on the control (conventional liquid electrolyte-based DSSC without PC film) and with PC film under light intensity of 100 mW cm^{-2} , are presented in Fig. 4. Triplicate determinations of the DSSC performance were carried out and the electrochemical properties are included in Table 1. The DSSCs assembled with the PC porous membrane report lower J_{sc} values than the control (13.08 mA cm^{-2} vs. 14.42 mA cm^{-2}). The lower J_{sc} value in the DSSC with PC may originate from its lower rate to supply I_3^- to the Pt counter electrode after PC incorporation. The PC film had a porosity of 10.51%, indicating that 10.51% of the space was filled with the

Table 1
Cell performance of as-prepared DSSCs^a with and without PC film.

Electrolyte support	J_{sc} (mA cm^{-2})	V_{oc} (V)	FF	Efficiency (%)
None	14.42 ± 0.70 ^b	0.70 ± 0.01	0.63 ± 0.01	6.34 ± 0.44
PC film	13.08 ± 0.82	0.70 ± 0.02	0.63 ± 0.03	5.75 ± 0.73

^a Single-sealed cells.

^b Mean ± standard deviation ($N=3$).

electrolyte. This fraction might not be as efficient as the liquid electrolyte for I^- and I_2 transport. This might have caused I_3^- depletion and retarded the dye regeneration kinetics [11]. Therefore, the J_{sc} was reduced in the PC-containing DSSC. There were no significant differences in the FF (both of 0.63) and V_{oc} (both of 0.70 V) between the DSSCs with and without PC film. The photovoltaic efficiency was 5.75% for the PC-containing DSSC, slightly lower than the control (6.34%).

3.3. Comparison with literature data

Table 2 lists the DSSC performance in the literature results, along with the data from this study. It clearly demonstrates that the photovoltaic efficiency is strongly dependent on the J_{sc} value. The V_{oc} and FF are in the comparable range among the literature data. Wei et al. proposed to decrease the film thickness and to increase ionic conductivity of the electrolyte impregnated film at the same time. The DSSC efficiencies using micro-porous supports were 3.46% and 4.31%, respectively, for 30 and 12- μm film at 100 mW cm^{-2} illumination. However, the performance was significantly lower than the liquid cell (efficiency of 5.11%) [13]. Kim et al. prepared acrylonitrile-methyl methacrylate (AN-MMA)-co-polymer membrane with porosity of 51% and film thickness of 50–60 μm [11]. In spite of their highly porous support, the film was thicker than most materials used in DSSCs. The low photovoltaic efficiency of 2.4% (at 100 mW cm^{-2} illumination) was therefore not surprising. Zhang et al. prepared smaller area DSSC (0.15 cm^2 compared with 0.25–0.28 cm^2 in other studies) and reported the conversion efficiency of the DSSC with gel membrane was 6.0% at an irradiance of 75 mW cm^{-2} , a lower efficiency than the cell with liquid electrolyte (8.6%) [12]. Chen et al. have shown that the conversion efficiency of 4.58% was obtained with poly(styrene-methyl methacrylate) (PS-PMMA) blend with a film thickness of only 1.66 μm [14]. Park et al. employed liquid impregnated polymer membranes into DSSC, forming quasi-solid-state electrolytes for highly efficient DSSC with an overall conversion efficiency of 8% at room temperature under 1 sun illumination [15]. In comparison, this study resulted in moderately high conversion efficiency (5.75%), probably due to the thinner membrane thickness and the straight cylindrical pore geometry [17]. The later facilitated higher ion transports than the tortuous path encountered in other films made by phase inversion method.

Table 2
Solar cell performance comparison by incorporation of porous polymeric film into DSSC.

Film material	Electrolyte	J_{sc} (mA cm^{-2})	V_{oc} (V)	FF	Efficiency on 0.25–0.28 cm^2 cell (%) (efficiency of liquid electrolyte-based cell)	Thickness (μm)	Ref.
AN-MMA ^a -co-polymer	0.5 M LiI, 0.05 M I_2 , 0.05 M TBP ^e in AN ^f	6.27	0.72	0.53	2.4 (2.8)	50–60	[11]
PVDF-HFP ^b	0.5 M LiI, 0.05 M I_2 , 0.5 M TBP in PC ^g	11.86	0.72	0.51	6.0 ^k (8.6)	30	[12]
PVDF-HFP/PEG/PEGDMA ^c	0.6 M DMPII ^h , 0.1 M LiI, 0.05 M I_2 , 0.5 M TBP in 3-MPN ⁱ	9.47	0.78	0.59	4.31 (5.11)	12	[13]
PS-PMMA ^d	0.6 M DMPII, 0.1 M LiI, 0.05 M I_2 , 0.05 M TBP in 3-MPN	11.68	0.70	0.56	4.58 (4.62)	1.66	[14]
PVDF-HFP	0.6 M BMII, 0.03 M I_2 , 0.1 M GTC, 0.5 M TBP in AN/VN	15.8	0.78	0.65	8.00 ^m (–)	20	[15]
PC ^e	0.6 M PMII ^j , 0.1 M LiI, 0.05 M I_2 , 0.5 M TBP in AN ^f	11.66	0.71	0.67	5.75 (6.34)	5–6	This work

^a Acrylonitrile-methyl methacrylate.

^b Poly(vinylidene fluoride-co-hexafluoropropylene).

^c Poly(vinylidene fluoride-co-hexafluoropropylene)/polyethylene glycol/polyethylene glycol dimethacrylate.

^d Poly(styrene-methyl methacrylate).

^e 4-Tert-butylpyridine.

^f Acetonitrile.

^g Polycarbonate.

^h 1,2-Dimethyl-propylimidazolium iodide.

ⁱ 3-Methoxypropionitrile.

^j 1-Methyl-3-propylimidazolium iodide.

^k The data was measured on DSSC with 0.15 cm^2 active area under 75 mW cm^{-2} illumination, whereas others were with active area of 0.25–0.28 cm^2 under 100 mW cm^{-2} .

^l Not available.

^m Cell area not specified.

3.4. Long-term cell performance of DSSCs

3.4.1. Light soaking at room temperature

The DSSCs with and without PC films were tested under illumination of 100 mW cm^{-2} (1 sun) after being aged in light soaking and 25 °C. The results of J_{sc} , V_{oc} , FF and efficiency were shown in Fig. 5. Although the DSSC with PC film had a lower efficiency at the beginning, the performance was higher than the control at 100 h of aging (Fig. 5d). The higher efficiency was ascribed to the higher photocurrent density (J_{sc}), as shown in Fig. 5a. The PC exhibited capillary force on the liquid within the pores and helped with solvent retention. As the DSSC aged, the liquid electrolyte evaporated soon in the control cells and the cell resistance increased. The current density decreased as a result. Therefore the inclusion of PC film is beneficial for DSSC lifetime.

3.4.2. Aging at 60 °C

For accelerating aging tests at 60 °C, the DSSCs were double-sealed in order to prevent electrolyte evaporation at the high temperature. Six control cells (without PC) and eight DSSCs with PC film were assembled. The cell performance was summarized in Table 3. The control cells exhibited J_{sc} of $12.77 \pm 0.71 \text{ mA cm}^{-2}$, V_{oc} of $0.67 \pm 0.01 \text{ V}$, FF of 0.68 ± 0.02 , and efficiency of $5.84 \pm 0.36\%$. The DSSC with PC film exhibited J_{sc} of $12.00 \pm 1.28 \text{ mA cm}^{-2}$, V_{oc} of $0.67 \pm 0.02 \text{ V}$, FF of 0.67 ± 0.01 , and efficiency of $5.54 \pm 0.66\%$. There were no significant differences in J_{sc} , V_{oc} , FF, and efficiency data between DSSCs with and without PC film. Half of the cells from each group were assigned to light soaking, the other half to darkness, as shown in Table 3.

The cells with and without PC film were measured for photovoltaic performance after light soaking at 100 mW cm^{-2} and 60 °C for up to 960 h. The J_{sc} , V_{oc} , FF, and efficiency data were shown in Fig. 6. The as-prepared control cells exhibited an average efficiency of 5.78% and the efficiency continued to decline over time: the average efficiency of 4.52% after 960 h, a 21.8% reduction (Fig. 6d). The PC-containing cells had an average efficiency of 5.52% and decreased to 4.32% (Fig. 6d) during a similar aging period. The reduction of the efficiency of the PC-containing cells was 21.7%, comparable to the control cells. Zhang et al. found that the energy conversion efficiency of a quasi-solid-state solar cell stored at 55 °C-oven decreased 23% after 192 h [12]. Sommering et al. [18] reported a 12–15% decrease in efficiencies after ~1200 h of continuous illumination of 1 sun at a moderate temperature (45 °C).

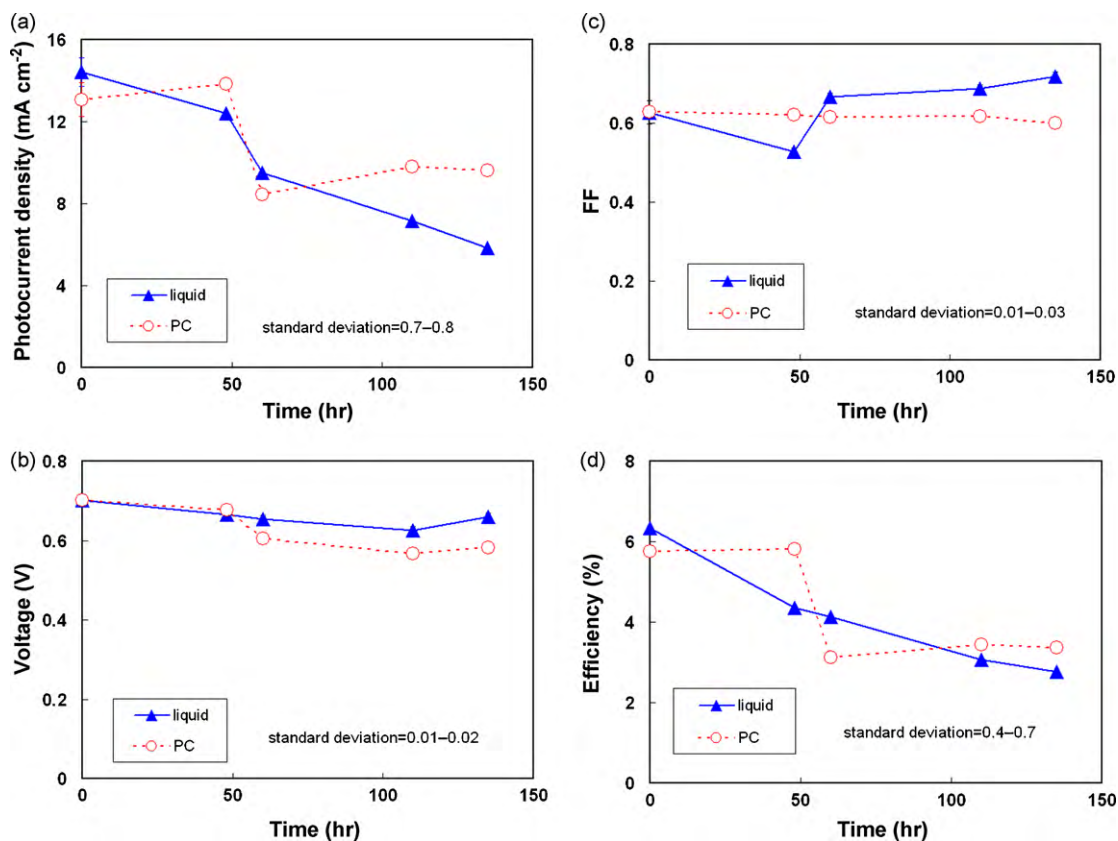


Fig. 5. Variations in (a) short-circuit photocurrent density, (b) open-circuit voltage, (c) fill factor (FF), and (d) efficiency as a function of elapsed time for dye-sensitized solar cells, assembled with liquid electrolyte and with PC micro-porous support, under illumination of 100 mW cm^{-2} (1 sun) after being aged in light soaking and 25°C .

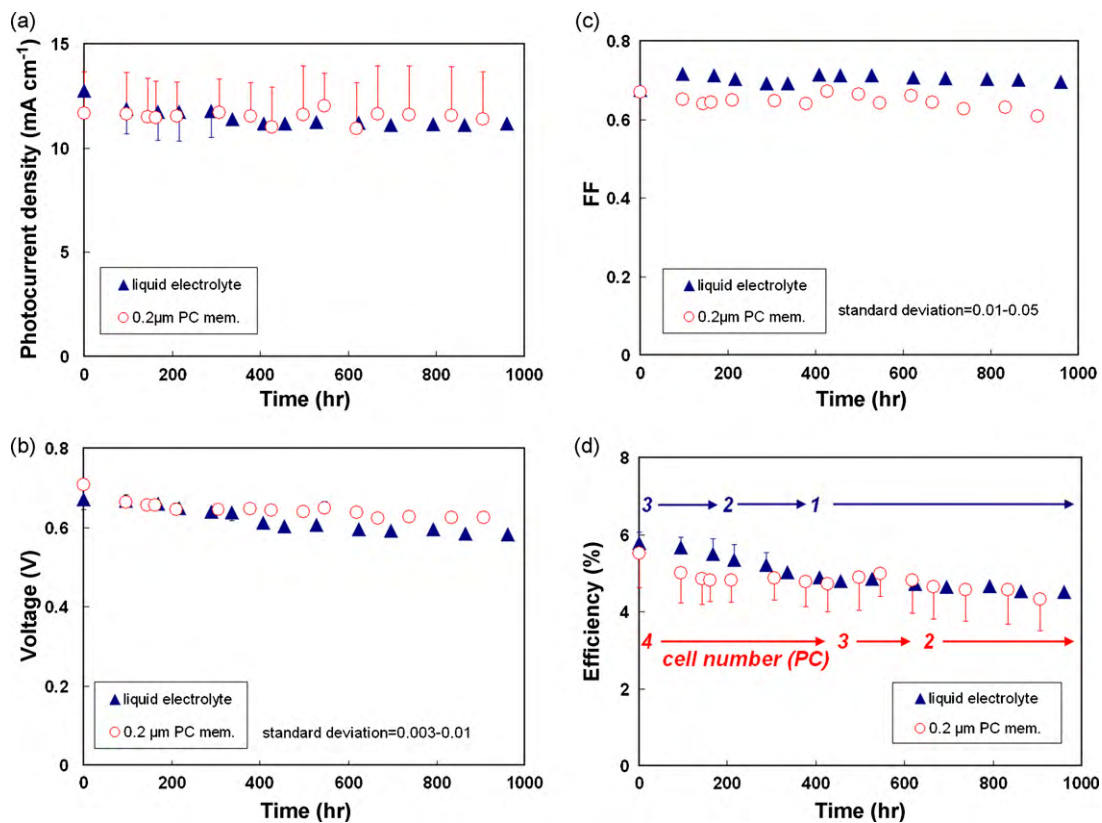


Fig. 6. Variations in (a) short-circuit photocurrent density, (b) open-circuit voltage, (c) fill factor (FF), and (d) efficiency as a function of elapsed time for dye-sensitized solar cells, assembled with liquid electrolyte and with PC micro-porous support, under continuous light soaking of 100 mW cm^{-2} (1 sun) and 60°C .

Table 3
DSSC^a assignments to light soaking and in darkness for high temperature stability test.

	J_{sc} (mA cm ⁻²)	V_{oc} (V)	FF	η (%)	Aging ^b
Liquid-1	12.726	0.652	0.651	5.40	L
Liquid-2	12.645	0.676	0.685	5.86	L
Liquid-3	12.794	0.689	0.699	6.16	L
Liquid-4	13.994	0.664	0.684	6.35	D
Liquid-5	11.778	0.679	0.703	5.62	D
Liquid-6	12.706	0.659	0.672	5.63	D
Average	12.774 ± 0.708	0.670 ± 0.014	0.682 ± 0.019	5.84 ± 0.360	
PC 0.2 μm-1	12.011	0.693	0.678	5.65	D
PC 0.2 μm-2	9.857	0.660	0.664	4.32	D
PC 0.2 μm-3	12.805	0.699	0.665	5.95	D
PC 0.2 μm-4	13.064	0.699	0.665	5.99	D
PC 0.2 μm-5	13.312	0.690	0.664	6.10	L
PC 0.2 μm-6	10.250	0.678	0.678	4.71	L
PC 0.2 μm-7	12.514	0.704	0.671	5.91	L
PC 0.2 μm-8	12.218	0.700	0.665	5.69	L
Average	12.004 ± 1.280	0.690 ± 0.015	0.669 ± 0.006	5.54 ± 0.658	

^a The cells were double-sealed for high temperature testing.

^b L, light soaking and D, in darkness.

The PC-containing cells exhibited better long-term stability than the quasi-solid-state solar cell. In this work the two types of cells (with PC film and without PC film) demonstrated similar J_{sc} (Fig. 6a). The PC-containing cells exhibited higher V_{oc} and lower FF values than the control cells (Fig. 6b and c). The number of the control cells (without PC film) was decreased from three to two at elapsed time of 216 h, as shown in the cell numbers in Fig. 6d. After 408 h only one remaining cell was functioning. However, all four of the PC-containing cells were working until 426 h, after which one cell broke down. After 618 h of operation, another cell ran out and the

remaining two cells were viable till the end of the test (Fig. 6d). The results demonstrated that the PC film could prevent liquid leakage and prolong cell life.

The cell performances of the DSSCs with and without PC film were also compared after storage in darkness at 60 °C and the results are shown in Fig. 7. The cell efficiency dropped significantly in the first 24 h, as shown in Fig. 7d. The average efficiency of the control cells decreased from 5.99% to 3.48% and the cells with PC film decreased from 5.66% to 3.21%. The reason accounted for the rapid drop in efficiency in the initial 24 h was not clear

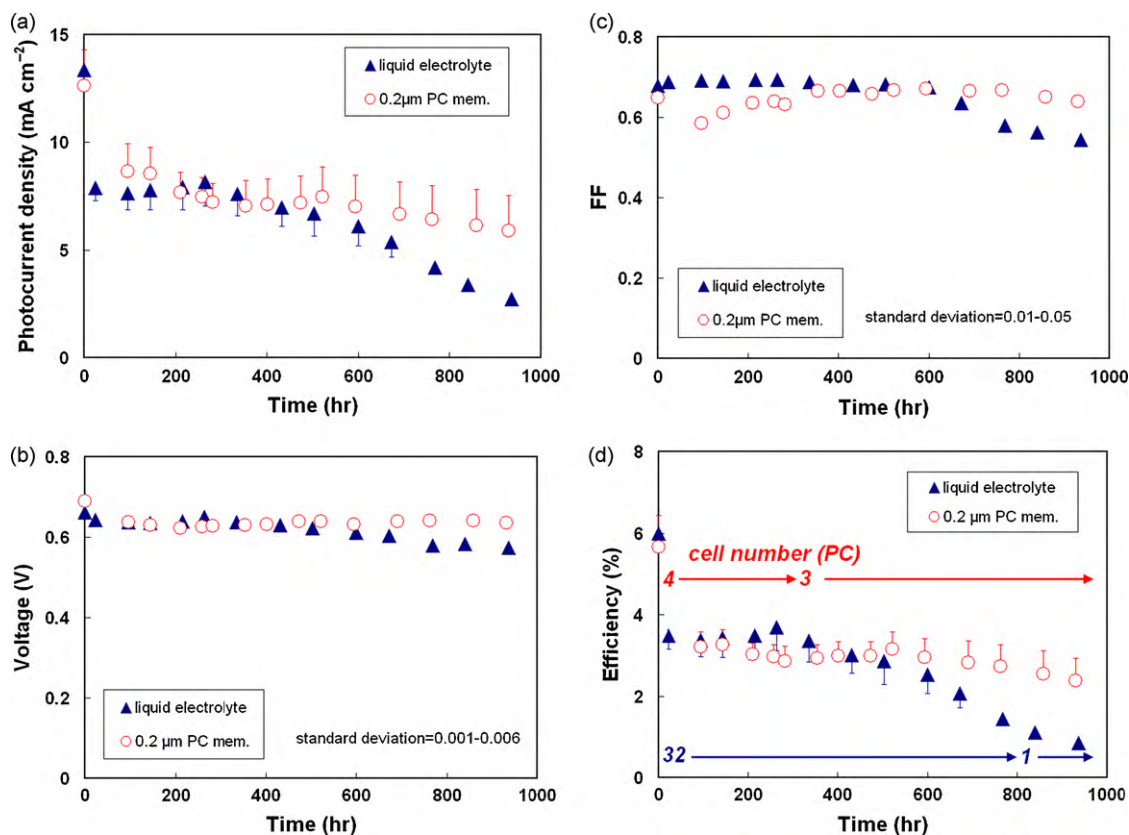


Fig. 7. Variations in (a) short-circuit photocurrent density, (b) open-circuit voltage, (c) fill factor (FF), and (d) efficiency as a function of elapsed time for dye-sensitized solar cells, assembled with liquid electrolyte and with PC micro-porous support. The solar cells were kept in darkness and 60 °C unless during testing period, which was conducted under illumination of 100 mW cm⁻² (1 sun) and 60 °C.

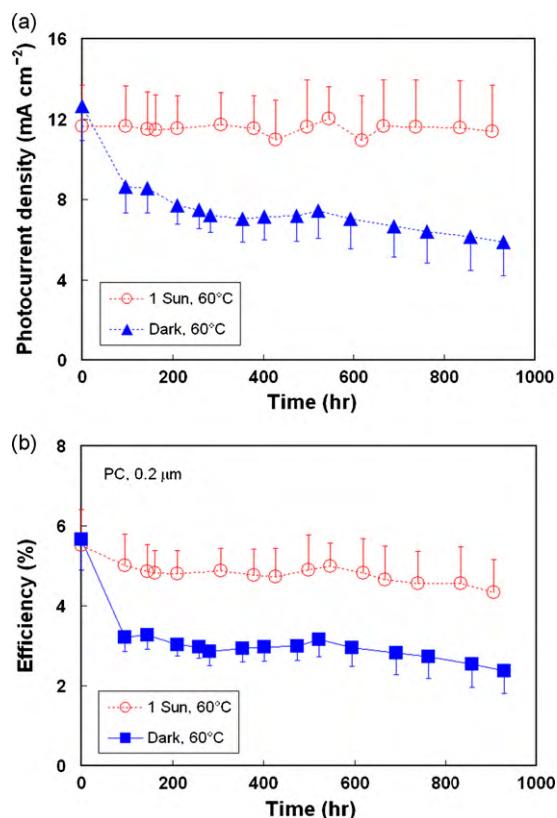


Fig. 8. Variations in (a) short-circuit photocurrent density, and (b) efficiency as a function of elapsed time for dye-sensitized solar cells, assembled with PC micro-porous support. The solar cells were kept in darkness or under 100 mW cm^{-2} (1 sun) illumination and 60°C .

at this time. Sommering et al. [18] reported that DSSC efficiency was decreased significantly at 85°C in darkness, but regained upon sun illumination. They ascribed this reversible phenomenon to an activation-controlled process, instead of solvent leakage. After 400 h, the PC-containing cells start to outperform the control cells. At the end of the aging test, the average efficiency of the control cells decreased to 0.85% (75.6% reduction) and the cells with PC film decreased to 2.37% (58.1% reduction). That efficiency changes were parallel to the trends in the J_{sc} decreases (Fig. 7a). The data in Fig. 7b and c also demonstrated that V_{oc} and FF were higher in the PC-containing cells than the control cells. The number of working control cells decreased from three to two right after 24 h of storage (Fig. 7d). At 840 h, another cell crashed and the remaining single cell stayed practicable till the end of the test. Conversely, one out of four PC-containing cells failed after 354 h. The remaining three cells worked throughout the experiment (Fig. 7d). Again, the incorporated PC film confirmed the enhanced cell durability in darkness.

The high temperature aging tests confirmed that the PC film helped electrolyte stability and prolonged cell life. Although the control and PC-containing cells exhibited similar cell efficiencies (Fig. 6) in light soaking conditions, their performance was different in a dark environment. Fig. 8a and b compares the J_{sc} and efficiency data, respectively, for the PC-containing DSSCs in darkness

and light soaking. The V_{oc} and FF values in different aging conditions, however, did not show differences. The DSSC with PC film was expected to demonstrate favorable results for daily life application, in which the cells are exposed to light and darkness alternatively.

4. Conclusion

This research investigated the cell performance and long-term stability of dye-sensitized solar cells (DSSCs) containing micro-porous polycarbonate (PC) film as the frame work material to stabilize electrolyte solution. The PC film exhibited good thermal stability and chemical compatibility with the organic solvent (acetonitrile). The light-to-electrical energy conversion efficiency of the DSSC with $0.2\text{-}\mu\text{m}$ PC membrane under 1 sun irradiation was slightly lower than that of cells without PC film (5.75% vs. 6.34%), although the difference was not statistically significant. The long-term cell performance was carried out at continuous illumination of 100 mW cm^{-2} (1 sun) and in darkness at 60°C for up to 1000 h. There was no significant efficiency difference between the cells with and without PC film in light soaking conditions (4.33% vs. 4.52%) for 960 h. In darkness, however, the cells with the PC film demonstrated much higher efficiency (at 2.37%) than the cells without PC (0.85%) after 1000 h. The higher efficiency was ascribed to the higher current density, open-circuit voltage, and fill factor. The improved long-term efficiency data and the higher percentage of working cells confirmed the superior lifetime and performance using the micro-porous PC film.

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