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Planate Conducting Polymer Actuator based on Polypyrrole and Its Application

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Abstract

In this study, we propose a planate actuator which can transform only its central part locally. We have developed a planate conducting polymer actuator based on polypyrrole (PPy) and two types of acids, such as *p*-phenol sulfonic acid and dodecylbenzene sulfonic acid, by electrodeposition. Its structure was patterned bimorph structure with anion-driven, cation-driven and bimorph layers. The planate conducting polymer actuator could deform only its central part locally. Moreover, we introduce a micro pump that operates by planate conducting polymer actuator as the drive source. The water level in the flow channel of micro pump shows the reciprocating motion measuring ±2 mm in accordance with the oscillation of the bimorph conducting polymer actuator

which was approximately 28 μl/min. The oscillating volume can be controlled by the application of electrochemical potential and its scan rate applied to the actuator.

Keywords : Conducting polymer, Actuator, Electrochemomechanical deformation, Micro pump

Introduction

The most outstanding feature of conducting polymer is drastic enhancement of electroconductivity upon oxidation and reduction. The conducting polymers can be utilized as a semiconductor device such as light emitting diodes, solar cells and transistors as well as metallic conductors. On the other hand, upon oxidization and reduction, the conducting polymers change physical properties as swelling or shrinking [1]. The variation of the dimension is induced by an electrochemical cycle, which is called electrochemomechanical deformation (ECMD) and can be utilized as a soft actuator and artificial muscles [2,3]. The soft actuator based on the conducting polymer has attracted much attention recently.

The authors have already reported the ECMD in conducting polymers, such as polyaniline (PAn) [4,5], poly(o-methoxyaniline) (PmAn) [6,7], poly(3-alkylthiophene)s [8] and polypyrroles (PPy) [9, 10, 11, 12]. In particular, ECMD of PPy freestanding films have been clarified sufficiently.

The electrodeposition is a simple way to obtain high quality PPy thin films. The electrochemical activity range of PPy films is found to be as wide as pH from 3 to 10 [9]. Takashima et al [13] investigated bimorph soft actuator by anion-driven layer and cation-driven layer in PPy film and large bending motions were observed in 1 M NaCl solution. Bay et al has improved electrochemical strain of PPy doped with dodecylbenzensulfonate (DBS) from 2.5% to 5.6% by the addition of pentanol as a co-surfactant to DBS [14], and from 5.6% to 12% by using a compliant gold electrode [15]. Hara et al [16] have developed a novel PPy actuator that induces maximum strain of 12-15 % and maximum stress of 18-22 MPa electrochemically. They have developed a PPy actuator that bends electrochemically with $TBACF_3SO_3$ as electrolyte, and the actuator showed force of 13.7 N. Moreover, they [17] have developed TFSI-doped PPy actuator and reported its maximum strain and maximum stress were 26.5 % and 6.7 MPa, respectively.

Recently, a various shapes of actuators based on the conducting polymer have also attracted attention. We have proposed ring type and lip type soft actuators, using bimorph soft actuator based on PPy [18]. Takashima et al [19] have developed patternable bi-ionic PPy actuator similar to a spring. Hara et al [20] have developed a polypyrrole-metal coil composite actuator and a PPy-zigzag metal wire composite actuator. Wu et al [21] have developed the Tube In Tube Actuator Node structure based on PPy for microfluidic pump. Ding et al [22] have reported that the tube actuators with helical wire interconnects provide up to 5% axial strain. Moreover, the conducting polymer actuator have been recently used in the construction of valves for microfluidic systems [23, 24].

In this study, we propose a planate actuator which can transform only its central part locally. We developed a planate actuator based on PPy using bimorph structure actuator by electrodeposition and measured displacement of central part on the actuator. Moreover, we introduce a micro pump that operates by the planate PPy actuator.

Experimental

Sample preparation

Planate PPy actuator films were electrodeposited from aqueous acids. A titanium (Ti) plate, a platinum (Pt) plate and a silver wire were employed as working, counter and reference electrodes, respectively, and *p*-phenol sulfonic acid (PPS) and dodecylbenzene sulfonic acid (DBS) were employed assupporting electrolyte for the electrodeposition in this study. Firstly, electrodeposition was performed on the central part measuring $15\times15mm^2$ of Ti plate measuring $30\times30mm^2$ by aqueous electrolyte solution containing 0.15 M of pyrrole monomer and 0.25 M of PPS. A region except for the central part on Ti plate is covered with insulating tape. The deposition was conducted in galvanostatic mode with 1 mA/cm^2 of current density for 2000 s at a room temperature. As shown in Fig. 1, the PPy.PPS film with a thickness of approximately 30μm was deposited on the central part of Ti plate.

Secondly, the insulating tape put on the area other than the central part of the titanium plate was pealed, the central part of PPy.PPS film measuring 7.5×7.5mm^2 was covered with insulated tape and the electrodeposition was performed on the Ti plate measuring 30×30mm^2 by aqueous electrolyte solution containing 0.15 M of pyrrole monomer and 0.25 M of DBS. PPy.DBS film with a thickness of approximately 30μm was deposited on the Ti plate, as shown in Fig. 1. Moreover, PPy.PPS/PPy.DBS film of the bimorph structure was deposited on the outside the PPy.PPS film and it was approximately 60μm in thickness.

Finally, the deposited PPy actuator film was peeled off from the Ti plate and we have obtained a planate PPy actuatore film, as shown in Fig. 1. Its structure was patterned bimorph structure with anion-driven, cation-driven and bimorph layers.

In order to investigate characteristics of the planate PPy actuator, we have also prepared other actuators, a single layer PPy actuator and a simple bimorph PPy actuator which were not patterned, as shown in Fig. 2 (a) and (b), respecively. The single layer PPy actuator was prepared by the electrodeposition with aqueous electrolyte solution containing 0.15 M of pyrrole monomer and 0.25 M of DBS. We have obtained a PPy.DBS actuator, as shown in Fig. 2 (a), and it was approximately 30μm in thickness. The bimorph PPy actuator was prepared by the patterning technique of bimorph structure. The electrodeposition was performed on the Ti plate measuring 30 × 30mm^2 with aqueous electrolyte solution containing 0.15 M of pyrrole monomer and 0.25 M of DBS and PPy.DBS actuator was deposited on Ti plate. PPy.PPS actuator measuring 7.5 × 7.5 mm^2 with aqueous electrolyte solution containing 0.15 M of pyrrole monomer and 0.25 M of PPS was electrodeposited on the central part of the PPy.DBS actuator. We have obtained the simple bimorph PPy actuator, as shown in Fig. 2 (b), the single and bimorph layers were approximately 30μm and 60μm in thickness, respectively.

Measurement setup

Displacement of the central part of the planate PPy actuator was measured by a laser displacement meter with accuracy of 8 μm (Keyence LB-1000), as shown in Fig. 3. In this study, the Pt plate and the silver wire were employed as counter and reference electrodes, respectively, and the outside of the planate PPy actuator was fixed by the Pt plates as the working electrode and Teflon plates, as shown in Fig. 1. The electrochemical potential was applied by a potentiostat (Hokuto Denko HB-105). The electrolyte solution was an aqueous 1.0 M sodium chloride (NaCl) solution. All data were supplied as analogue voltages and converted to digital data by an A/D converter. In the displacement of the actuators, the positive and negative values indicate the deformation to laser displacement meter and counter electrode sides, respectively, as shown in Fig. 4.

Results and discussion

Deformation of planate PPy actuator

Figure 5 shows cyclic voltammetry (CV) curve and the displacement of the central part of the planate PPy actuator. A broken line, a dash-dotted line and a solid line show the results from single layer, bimorph and patterned bimorph PPy actuators, respectively. Application of electrochemical potential was from –1.1 [V] to 0.6 [V] and its scan rate was 20 [mV/sec]. The arrows indicate the moving direction of current and displacement. The current and displacement data for one hundred cycles were translated into averaged data for one cycle.

In the CV curve results oxidation and reduction peaks are found at approximately 0.3 [V] and –0.6 [V], respectively, in all planate PPy actuators. The current obtained during CV of patterned bimorph PPy actuator was larger than that of single layer and bimorph PPy actuators.

The central part of the single layer PPy actuator oscillated in the range of ±0.5 [mm]. The oscillation of the central part of bimorph actuator became as large as ±1.0 [mm]. The deformation of the bimorph PPy actuator was larger than that of single layer actuator by the same principle of a beam type bimorph PPy actuator[13)]. In patterned bimorph PPy actuator, moreover, the central part oscillated approximately ±2.5 [mm]. The deformation of patterned bimorph PPy actuator became larger than that of single layer and bimorph PPy actuators. The central part of PPy actuator deforms toward the laser displacement meter at the oxidized state and deforms toward the counter electrode at the reduced state. It is found that the anion-driven layer on the central part of the planate PPy actuator deforms predominantly.

Figure 6 shows the displacement of the patterned bimorph PPy actuator. The solid and dash-dotted lines show the results from the anion layer and the bimorph layer. The displacement of the anion layer on the central part of the planate PPy actuator was larger than that of bimorph layer and the outside of the actuator, the cation layer, did not deform. More specifically, it was clarified that only the central part of the planate PPy actuator could deform locally.

Figures 7 (a) and (b) show the cross-section drawings of planate PPy actuators, such as bimorph and patterned bimorph actuators, respectively. In the case of the bimorph actuator, as shown in Fig. 7 (a), the anion layer actuator expanded due to the insertion of anion, Cl^-, and the cation layer actuator shrunk due to the extraction of cation, Na^+, in the oxidation. Furthermore, the anion layer actuator shrunk due to the extraction of Cl^- and the cation layer actuator expanded due to the insertion of Na^+ in the reduction. These mechanisms were the same as the case of beam type bimorph PPy actuator[13]. In the case of the patterned bimorph PPy actuator, on the other hand, the central pat of the planate PPy actuator was easy to deform since the central part was a single anion layer and the outside of the anion layer was bimorph structure, as shown in Fig. 7 (b). Therefore, the deformation of the central part became large.

Figure 8 shows the relationship between the maximum displacement and the frequency of the central part of the planate PPy actuators. The broken and solid lines show the results in bimorph and patterned bimorph actuators, respectively.

The maximum displacements of both planate PPy actuators were inversely proportional to its frequency. In other words, the maximum displacement decreased as its frequency increased. The maximum displacement of the bimorph PPy actuator was ±1.0 mm at 0.006 Hz and the oscillation can be periodic up to 0.6 Hz. However, the displacement was extremely small and we have not obtained the periodical oscillation over 0.6 Hz. On the other hand, the maximum displacement of the patterned bimorph PPy actuator was ±2.1 mm at 0.006 Hz and the oscillation can be periodic even at 3.0 Hz. The maximum displacement of the patterned bimorph PPy actuator becomes larger than that of the simple bimorph actuator in all frequencies.

Micro pump by planate PPy actuator

We have proposed a micro pump using a patterned bimorph PPy actuator. A tank measuring 20×20×3 mm^3 was placed in an acryl plate measuring 30×30×5 mm^3 and a flow channel with a diameter of 3 mm was connected with the tank, as shown in Fig. 9. The patterned bimorph PPy actuator as a drive source was connected with the bottom of the tank, as shown in Fig. 10. A vinyl sheet with a thickness of 100 μm was placed between the patterned bimorph PPy actuator and the bottom of the tank, and the outside of the patterned bimorph PPy actuator was fixed to the platinum plates. The Pt plate and the silver wire were employed as counter and reference electrodes, respectively, as shown in Fig, 10, and an aqueous 1.0 M sodium chloride (NaCl) solution was used as an electrolyte solution. The distilled water was filled in the tank and the flow channel. This pump was not connected with the valve and we have measured the oscillating volume by calculating the water level in the flow channel oscillated by the patterning bimorph PPy actuator.

Figure 11 shows the change of water level in the flow channel. The application of electrochemical potential was from –1.1 V to 0.6 V and its scan rate was 20 mV/sec. The water level in the flow channel shows the reciprocating motion measuring ±2 mm in accordance with the oscillation of the pattered bimorph PPy actuator which was approximately 28 μl/min. The oscillating volume can be controlled by the application of electrochemical potential and its scan rate applied to the actuator. It is well known that the required flow rate is from 1.0 to 50.0 μl/min for a μ-TAS system and an insulin pump [25, 26]. The micro pump proposed by our study can satisfy these flow rates and the authors presume that it can be applied to micro pumps.

Conclusions

We have developed a planate conducting polymer actuator based on polypyrrole (PPy) and two types of acids, such as *p*-phenol sulfonic acid and dodecylbenzene sulfonic acid, by electrodeposition. Its structure was patterned bimorph structure with anion-driven, cation-driven and bimorph layers. The planate conducting polymer actuator could deform only its central part locally.

And, we have proposed a micro pump using the planate conducting polymer actuator as the drive source. The water level in the flow channel of micro pump shows the reciprocating motion measuring ±2 mm in accordance with the oscillation of the bimorph conducting polymer actuator which was approximately 28 μl/min. The oscillating volume can be controlled by the application of electrochemical potential and its scan rate applied to the actuator. It is well known that the required flow rate is from 1.0 to 50.0 μl/min for a μ-TAS system and an insulin pump. The micro pump proposed by our study can satisfy these flow rates and the authors presume that it can be applied to micro pumps.

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Biography

Masaki Fuchiwaki received his B. Eng., M. Eng., and Dr. Eng. degree in Mechanical Engineering from Kyushu Institute of Technology in 1994, 1996 and 2000, respectively. He was a researcher at Osaka Science & Technology Center. He became a Research Associate at the Department of Mechanical Information Science and Technology at Kyushu Institute of Technology in 2002. He is currently an associate professor in the Department of Mechanical Information Science and Technology at Kyushu Institute of Technology.

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