Microvalves Based on Ionic Polymer-Metal Composites for Microfluidic Application

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Simple and highly efficient microvalve systems based on an ionic polymer-metal composite (IPMC) diaphragm actuator have been developed. The microvalve system that was fabricated in this work operates when open and close voltage is applied, due to the phenomena of lithium ion flux and the subsequent electro-osmotic drag of water to the cathode. IPMC was prepared by compositing with platinum nanoparticles on both sides of Nafion™ thin film. SEM images of the IPMC showed the high density and uniform size distribution of the Pt nanoparticles in the interpenetrating layer to ensure the proper performance of an IPMC actuator. The displacement of the IPMC for the microvalve was measured with a laser displacement meter. The application of open and close voltage made the operation of the valve faster. The fluorescence images of the flow in the fabricated IPMC-based microvalve system showed the successful operation of flow control in the microfluidic channel. The IPMC-based microvalve system shows a potential of IPMC for application as an actuator in microfluidic systems.

Keywords: Ionic Polymer-Metal Composite (IPMC), PDMS Microchannel, Microvalve, Microfluidic Components.

1. INTRODUCTION

A typical micro total analysis system (μ-TAS) and lab-on-a-chip system require components such as pumps, valves, and mixers for the effective manipulation of fluids. Such components are actuated by pneumatic, thermopneumatic, hydraulic, piezoelectric, electromagnetic, or electrostatic displacements.1,2 Most of the conventional actuators for microvalve and micropumps are complex and expensive due to their sophisticated systems requiring precise control. Electroactive-polymer (EAP) actuators, on the other hand, are known to have flexibility and large deformation in spite of their slow response. These advantages of EAP ensure high actuator performance and provide a cost-effective solution to many actuator applications.3–8 The fabrication methods of and most concepts related to IPMCs were proposed by Oguro et al.3 and Shahinpoor et al.4 The effect of electrolytes and mobile cations on IPMCs was also investigated by them. The role of nanosized platinum particles in the performance improvement of IPMCs was studied by Kim et al.9 Onishi et al.10 proposed that via adsorption-reduction cycling, a nanoscale interpenetrating metal layer with a high interfacial area can be obtained within the polymer membrane. The application of an operating voltage causes lithium ion flux and the subsequent electro-osmotic drag of water to the cathode, which results in swelling at the cathode side due to water enrichment and shrinkage at the anode side owing to water depletion. These phenomena induce the bending motion of IPMCs, which is necessary for the open/closed control of the IPMC-based microvalve system, as shown in Figure I(a).

In this study, simple and highly efficient microvalve systems were designed and fabricated by employing an IPMC actuator. A schematic illustration of the open/closed
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2. EXPERIMENTAL DETAILS

2.1. Preparation of IPMC

Nafion™ (NE 1110, DuPont Co.), a 254-µm-thick perfluorosulfonic-acid membrane, was used for the ionic-polymer membrane of IPMC. IPMCs were fabricated following the procedure proposed by Millet.11 For the enhancement of the blocking force, the Nafion membrane was treated with DRIE (deep reactive-ion etching) under the following conditions, as shown in Figure 2(a): 50 sccm oxygen flow rate, 240 W, and 50 mTorr for 2 min, under a metal shadow mask with a pattern of equally distributed stripes (200-µm-wide slits and a 100-µm-wide barrier). The etched Nafion had trenches on the electrode surface [see Fig. 2(b)], which increased the surface area and helped the IPMC bend more easily.12

2.2. Fabrication of the IPMC-Based Microvalve

The fabrication process of microvalve systems based on an IPMC diaphragm actuator is illustrated in Figure 3. The IPMC-based microfluidic-valve system was fabricated via PDMS casting and replica molding. A PDMS microchannel pattern was fabricated using the standard soft lithography and PDMS molding techniques. First, a negative
photoresist (SU-8 50, Microlithography Chemical Corp.) was spin-coated on a silicon wafer at 500 rpm for 10 s, and at 2,500 rpm for 30 s. To remove the solvent from the photoresist and to harden the remaining photoresist, the wafer was soft-baked at 65 °C for 5 min, and at 90 °C for 15 min. The wafer was exposed to I-line UV light for 60 s (300 mJ/cm²), in a mask aligner system (CA-4/6M, SHINUMST Co., Ltd.). Post-baking was carried out at 65 °C for 1 min, and at 90 °C for 4 min. The photoresist was then developed with an SU-8 developer, washed carefully with isopropyl alcohol, and then dried with nitrogen gas. A PDMS mixture of a base and a curing agent (Sylgard 184, Dow Corning Corp.) in a 10:1 ratio was poured onto the developed SU-8 master pattern and was cured at 70 °C for 4 h. The cured PDMS was then detached from the wafer for use as a PDMS replica.

A glass substrate was treated with piranha solution (3:1 mixture of concentrated sulfuric acid (H₂SO₄) and 30% hydrogen peroxide (H₂O₂)) to remove the organic impurities and to generate a hydrophilic surface. Prior to bonding with a glass substrate, the PDMS replica was activated via O₂ plasma treatment to generate hydroxyl groups (except the region for valve on/off operation) via shadow masking. The PDMS replica was then attached to the glass substrate and was annealed at 65 °C for 6 h in an oven. A 2.5(W) × 3(L) × 0.25(T)-mm³ IPMC was fixed on the PDMS. An additional PDMS mixture was poured onto the IPMC to form the structure shown in Figure 1(b), after which the IPMC was cured at 65 °C for 6 h.

3. RESULTS AND DISCUSSION

The degree of interpenetration and the distribution of the electrode nanoparticles in the polymer matrix are crucial to the performance of an IPMC actuator. Therefore, the IPMC composition that was used in this paper was analyzed via SEM. The cross-sectional and surface images of the IPMC (Fig. 4) show that the thickness of the whole IPMC and the nanoscale conductive surface layer (Pt electrode) with a uniform surface were about 250 µm and 180 nm, respectively. The sizes of the Pt nanoparticles in the interpenetrating layer of the IPMC ranged from 50 to 100 nm, as shown in Figure 5. The SEM analysis showed the high density and uniform size distribution of the Pt nanoparticles, which can lead to uniform electric-current distribution through the IPMC, to ensure the proper performance of an IPMC actuator.

The bending characteristics of the IPMCs used in the microvalve system were measured with a laser displacement meter (LK-G30, KEYENCE), as shown in Figure 6. The laser displacement sensor was positioned in such a way that the laser beam was projected to a spot 1 mm away from the terminal of the electrode connection. The actuation of the microvalve was controlled using PC LabVIEW DAC-board (PCI6229, NI Co.), with an amplitude of 5 V. In the case of voltage-on (+5 V) for 4 s and voltage-off (0 V) for 236 s per cycle, the microvalve opened rapidly and closed slowly, as shown in Figure 6(a). The open/close operation of the microvalve was precisely controlled, however, when a reverse voltage (−5 V) for the closed state was applied for 1 s after applying an open voltage, as shown in Figures 6(b) and (c). Furthermore, the valve-open period depended directly on the open-voltage application time, showing the possibility of precise flow control in microfluidic devices. The displacement shown...
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Fig. 6. Displacement of the IPMC at (a) voltage-on for 4 s and voltage-off for 236 s, (b) voltage-on for 3 s, reverse voltage-on for 1 s, and voltage-off for 16 s, and (c) voltage-on for 10 s, reverse voltage-on for 1 s, and voltage-off for 19 s.

The displacement of the IPMC in Figure 6 is about 80–150 μm, large enough to cover the height (10 μm) of the structures in the usual microfluidic devices and to qualify IPMC for use as an actuator for microvalve systems. The response time was made less than 1 s to allow movement from the bottom to the top of the microchannel (~45 μm).

A schematic illustration of the microfluidic system is shown in Figure 7(a). An aqueous solution containing fluorescent polystyrene beads (0.5 μm mean particle size; Sigma-Aldrich Inc.) was injected into the inlet port with a syringe pump (Kd Scientific Inc.), and the images of the valve-open and valve-closed conditions were observed with the use of a fluorescence microscope (TE2000-U, Nikon Inc.) with an RFP filter (max excitation/emission = 553/574 nm) and was analyzed by ImageJ (a Java software for image processing and analysis), as shown in Figures 7(b) and 8. When the valve is closed, fluid flows from the inlet to the drain, and when the valve is open, fluid flows from the inlet to the outlet. Fluorescence was not observed across the valve during the valve-closed state, whereas strong fluorescence was observed in the valve-open state, as in Figure 7(b). Fluorescence images of the polystyrene bead flow (0.01 ml/min) in time were obtained after applying an open voltage, as shown in Figure 8. When an open voltage was applied in the valve-closed state [Fig. 8(a)], fluid began to flow to the outlet rather than to the drain, and the strong fluorescence observed in the moving gate valve indicated the opening of the valve, as shown in Figures 8(b) and (c). The gate valve was closed by applying a closed voltage, after which the fluorescence in the moving gate valve disappeared, as shown in Figure 8(d). The displacement of...
the microvalve can be precisely controlled by controlling the open and close voltage. These results suggest that IPMC-based microdevices are promising candidates for microfluidic-valve components.

4. CONCLUSIONS

A simple and highly efficient microvalve system based on an IPMC diaphragm actuator was developed. The bending characteristics of IPMCs in the microvalve were measured with a laser displacement meter, and the images of the valve-open and valve-closed conditions as well as of fluid control were observed via fluorescence microscopy. The IPMC-based microvalve system was operated via the displacement of the IPMC when open and close voltage was applied. The IPMC-based microvalve system has potential for application as an actuator in microfluidic systems.

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References and Notes


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