Fabrication of ionic-polymer-metal-composite (IPMC) micropump using a commercial Nafion

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ABSTRACT

This paper describes the fabrication and characteristics of an ionic polymer-metal composite (IPMC) membrane-shaped micro-actuator and its application to the fabrication of a micro-pump. After fabricating two 8㎜×8㎜ IPMC membrane-shaped actuators using a Nafion film, their displacements were measured. The fabricated IPMC membrane-shaped micro-actuators showed displacement of 14～27㎛ at the applied voltage ranging from $4V_{P-P}$ to $10V_{P-P}$ at 0.5Hz. Displacement of the IPMC actuator fabricated with a commercially available Nafion is large enough to make the IPMC actuator a membrane-shaped micro-actuator for fabricating an IPMC micro-pump. IPMC micro-pump was fabricated by assembling IPMC membrane-shaped micro-actuator and PDMS(polydimethylsiloxane) micro-channel together. PDMS micro-channel was designed to have nozzle/diffuser structures which make the fluids flow from inlet to outlet when the IPMC membrane-shaped micro-actuator is deflected up and down by the applied voltages. The measured flow rate of the fabricated IPMC micro-pump was about 9.97㎕/min at 0.5Hz when the input voltage and duty ratio were $8V_{P-P}$ and 50%, respectively. The test results illustrate that the fabricated IPMC micro-pump is suitable for pumping fluid through micro-channel on a PDMS substrate. Mechanical performances of beam-shaped and bridge-shaped conductive polymer actuator in aqueous solution and in solid electrolyte have been measured and analyzed. The optimum thickness of polypyrrole for the best bending performance is about 17-19 μm which has been polymerized at the current density of 5.4 $\mu A/mm^2$ for 120 minutes. For the application of conductive polymer actuator to a micropump, silicon bulk micromachining process has been combined.

Keywords: Polypyrrole, Solid polymer electrolyte, Parylene, Actuator, Micropump

1. INTRODUCTION

Ionic polymer metal composite (IPMC) generally consists of a perfluorinated polymer electrolyte sandwiched by electroplated platinum (Pt) on both sides. Two of the most popular base polymer fiilms are Nafion® (perfluorosulfonate, made by DuPont) and flemion (perfluorocarboxylate, made by Asahi Glass in Japan). IPMC can be used either for a sensor or for an actuator application because a slab of IPMC bends when an electric field is applied and it also can generate electric field when it is bent suddenly[1,2]. IPMC is considered as a candidate material for an actuator to be used in human body because it is known to be bio-compatible, soft, and functional under wet condition. In addition, IPMC has shown a large deformation in the presence of low applied voltage (1-2 V), fairly quick response (> 120 Hz), consecutive bending more than 100,000 times, and versatility of being fabricated in various shapes and sizes. When IPMC is operated, it doesn't generate either excessive heat or electromagnetic wave and hence its use has been investigated in biomechanical area, biomimetic area, or artificial muscle[3,4]. Osada et. al. demonstrated that the IPMC can be used as part of a catheter or an actuator of an elliptical friction drive (EFD)[5,6]. Caldwell et. al. showed the

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application of the IPMC into making an artificial muscle while Shahinpoor et. al. proposed its application into a peristaltic pump, human muscle supporter, or a robot fish[7,8]. Bar-Cohen et. al. demonstrated the use of the IPMC in the space-based applications because its actuation part is very simple and hence it is proper in the harsh environment where its maintenance and repair are quite difficult[9,10]. In most of these applications, the IMPC strip was used and a membrane-type IPMC was not often used.

Guo et. al. proposed a capsule-type micro pump by using IPMC membrane actuators with the advantages of the IPMC that were described above[11]. Their micro pump was fabricated by electroplating both sides of a commercially available Nafion® (perfluorosulfonate, made by DuPont) with Pt in order to make a membrane-type IPMC actuator and assembling it with pump structure. One of the disadvantages of the IPMC made with a commercially available Nafion® is that its thickness variation is limited by the manufacturer and a thick membrane can hardly be obtained this way. Also, Pt electroplating and the fabrication of the pump structure should be performed separately and they should be assembled later, which makes the process inconvenient.

This paper presents the fabrication of a IPMC micro actuator structure using a micro-electro-mechanical-systems (MEMS) fabrication process, proposes an IPMC membrane fabrication process which excludes extra assembly step by casting liquid Nafion® on this structure, and shows the measured displacement data of the IPMC membrane-type actuators with several size depending on the applied voltage.

2. EXPERIMENTS AND RESULTS

2.1. IPMC actuator material and working principle

For the preparation of IPMC actuator, Nafion® film was used as a solid polymer electrolyte. Solid polymer electrolyte is a solid material, which can conduct electrical current by the ionic movement in the material. In particular, Nafion® is a copolymer of polytetrafluoroethylene (PTFE) and sulfonyl fluoride vinyl ether, and it has the structure as shown in Fig. 1.

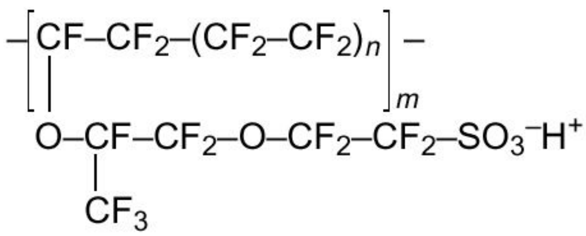


Fig. 1. Structure of perfluorosulfonic acid membrane

The polytetrafluoroethylene in the Nafion® provides a 3-dimensional structured backbone system having regularly spaced long perfluorovinylether pendant side chains which terminate in the ionic surfonate group (SO_3H). The ionic groups tend to aggregate to form tightly packed regions which are referred to as clusters. They are fully interconnected and are readily saturated by water. The membrane is permeable to water and cations while it is impermeable to anions[1].

The essence of electromechanical deformation of such polymer solid electrolyte systems is their susceptibility to the interactions with the externally applied fields as well as their own internal field structure. The mechanism of the bending motion of the solid polymer electrolyte is due to uni-directional electro-osmosis by cations, which their water solvent sheath, toward the cathode as illustrated in Fig. 2. Water enrichment at the cathode and depletion at the anode cause bending due to differential swelling and shrinkage[12,13].

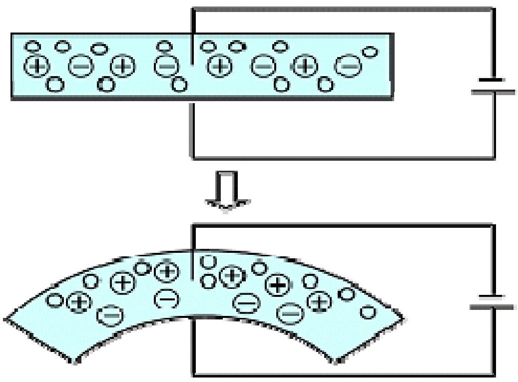


Fig. 2 Bending motion of IPMC actuator by applying the electric field.

2.2. Casting process and fabrication of a membrane-type IPMC actuator using liquid Nafion®

Typical thickness of a commercialized Nafion® film ranges from 50 to 180 μm. In order to achieve a desired thickness of Nafion® film other than the manufactured Nafion® with a fixed thickness, a casting was used. The casting method is a fabrication method of fabricating a solid Nafion® film out of liquid Nafion®. The overall casting step can be divided into several steps as illustrated in Fig. 3. In the first step, liquid Nafion® solution (EW 1000. Dupont) was prepared without any bubbles and it was poured into a casting frame about 8-9 times the desired final thickness. The Nafion® solution in the frame was dried out completely in the air and the dried Nafion® film was stripped off the frame. This Nafion® film was then thermally treated in order to increase the mechanical stiffness of the cast Nafion® film by increasing bonding strength of the molecules. After that, the cast Nafion® film was boiled in the hydrogen peroxide solution at 75 – 100 °C for an hour and again boiled in the de-ionized (DI) water for 1 hour [14].

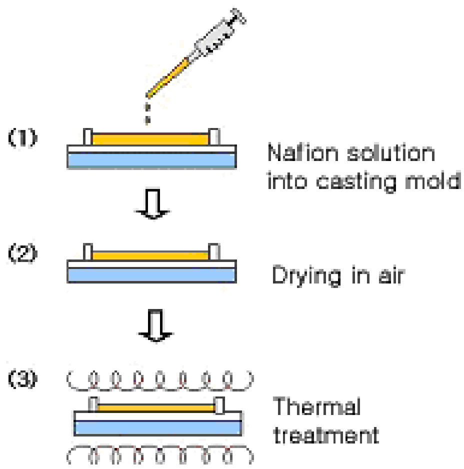


Fig. 3 Casting process of liquid Nafion

A membrane-type IPMC micro actuator can be fabricated by using the casting process shown in Fig. 3. The fabricated IPMC membrane-type actuator can be cut into a desired form and assembled with a pump structure to complete the formation of an IPMC micro pump. When the casting process can be integrated with the pump structure fabrication process, it is expected that the reproducibility of the IPMC micro pump would enhance. Therefore, various methods have been tried to fabricate an IPMC membrane on a silicon cast, which can be made by silicon anisotropic wet etching, so that the IPMC membrane-type actuator can be fabricated with a pump structure in one process and the assembly process can be excluded. Figure 4 shows the fabrication procedure for a silicon micro pump using IPMC membrane-type actuator. The designed micro pump consists of two parts – the upper part for holding the IPMC membrane mechanically and the lower part as a cast mold for making an IPMC membrane. They are fabricated separately and bonded later on. The upper part can be made of 4-inch, p-type, 500-μm thick (100) silicon wafer. Both sides of this wafer are thermally oxidized and patterned using a photolithography process to open the etch windows which are the same area as the IPMC membrane forming area. After removing the exposed thermal oxide, the silicon wafer is etched through with tetramethylammonium hydroxide (TMAH) solution. The lower part can also be made of 4-inch, p-type, 500-μm thick (100) silicon wafer and this wafer is also thermally oxidized and patterned on both sides. However, this wafer is not etched through but etched partially so that an IPMC membrane with a desired thickness can be obtained. The Nafion® membrane of a desired thickness is made on one side of this wafer by casting process, the silicon under the Nafion® membrane is etched away with TMAH in order to expose both sides of the NafionP® membrane. These two wafers are then bonded together by using epoxy and the Nafion® is converted to IPMC after electroless plating of Pt on the exposed Nafion®. The bonded wafers are then diced into a single pump unit and the channels are attached to complete the pump fabrication.

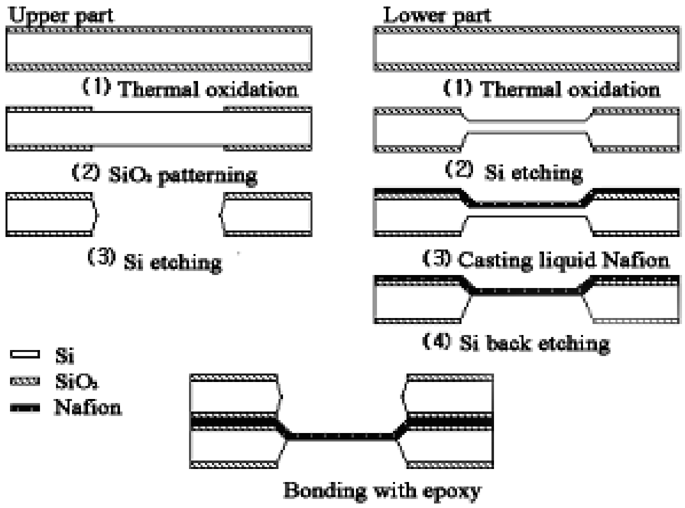
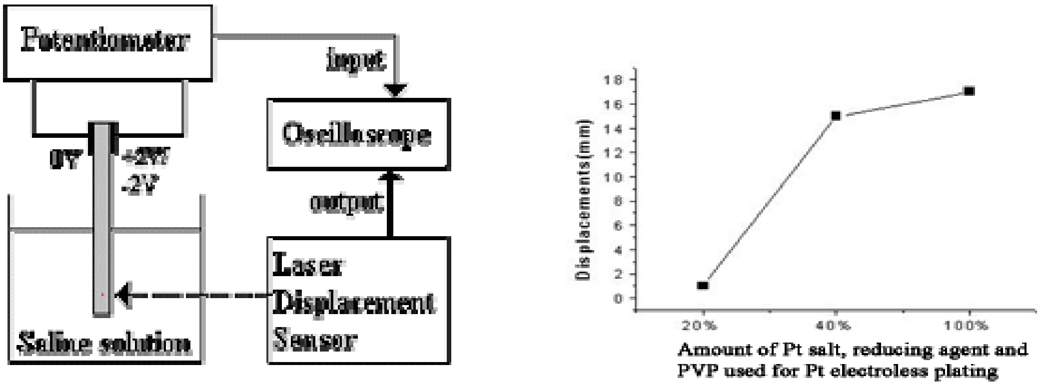


Fig. 4 Fabrication process of IPMC micro-actuator using Nafion solution casting

2.3. Fabrication of a membrane-type IPMC actuator and its characteristics

Fabrication of the IPMC membrane actuator with silicon micro pump structure at the same time was achieved. However, the function of the fabricated micro pump with IPMC membrane actuator was not as good as expected due to imperfect sealing between IPMC membrane and Silicon. Therefore, IPMC membrane was fabricated using Nafion® 112 instead and it was assembled with silicon pump structures in order to demonstrate that the IPMC membrane can operate a micro pump. In order to use the IPMC membrane-type actuator, it would be better to use a thin Nafion® film because a thinner IPMC membrane would have more deflection than a thicker membrane. The electroplating process developed before[3] was good for a thick IPMC file such as Nafion® 117 which is about 180 μm. In order to perform electroplating Pt on a thinner Nafion®, such as Nafion® 112 which is about 50 μm, a different electroplating process needs to be used and hence several experiments were performed for finding more proper electroplating condition. By reducing the adsorbing Pt complex on the Nafion film surface, the reducing solution, and the developing agent, the electroplating was completed successfully and the electroplated IPMC film was cut into a strip for the bending measurement.

The IPMC actuator made of Nafion® 112 was cut into the dimension of 4 mm in width and 30 mm in length. Before performing the displacement testing, the IPMC strip was kept in the DI water long enough to contain sufficient water in the IPMC. Its surface, however, was cleaned and wiped thoroughly with proper cleaners before the measurement. Figure 5(a) shows the bending measurement set-up with a laser displacement sensor and Fig. 5(b) shows the measured displacement data of the electroplated Nafion® 112 depending on the amount of the Pt complex, reducing agent, and the developing agent when they are 1/5 and 2/5 of the solution amount that was used for Nafion® 117. From this data, it was observed that when only 2/5 of the electroplating solution was used, the 50 μm thick Nafion® 112 can generate almost identical displacement to that of the electroplated Nafion® 117 film. However, when 1/5 of the electroplating solution was used, the displacement reduced significantly and hence the electroplating solution for Nafion® 112 was reduced to 2/5 of the amount used for Nafion® 117.



(a) (b)

Fig. 5 (a) Displacement measurement set-up of IPMC strip
(b)Displacement of IPMC versus amount of Pt salt, reducing agent and PVP used for Pt electroless plating,

In order to use the IPMC actuator in a micro pump, the actuator should be made to a membrane-type and its characteristics are more important than the characteristics of an IPMC strip. Therefore, the fabricated IPMC membrane as shown in Fig. 4 was tested and its characteristics were measured with the measurement set-up shown in Fig. 6. A laser displacement meter (KEYENCE LC-2450A) was focused to the center of the IPMC membrane and AC voltage was applied to the IPMC membrane actuator. Because the measured displacement is converted into a voltage by a laser displacement meter, the output can be measured using an oscilloscope and the data can be saved into a computer. A 8 mm x 8 mm IPMC membrane was made using 50-μm thick Nafion® 112 and its displacement was measured after applying $4V_{P-P}$, $6V_{P-P}$, $8V_{P-P}$, or $10V_{P-P}$ sinusoidal waveform at 0.5Hz, respectively. The measured data is shown in Fig. 7.

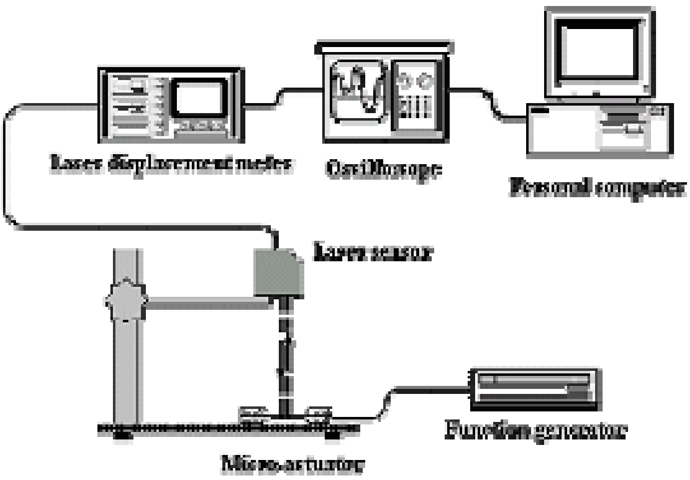


Fig. 6 A schematic picture of a displacement measurement system of IPMC membrane-type micro-actuator

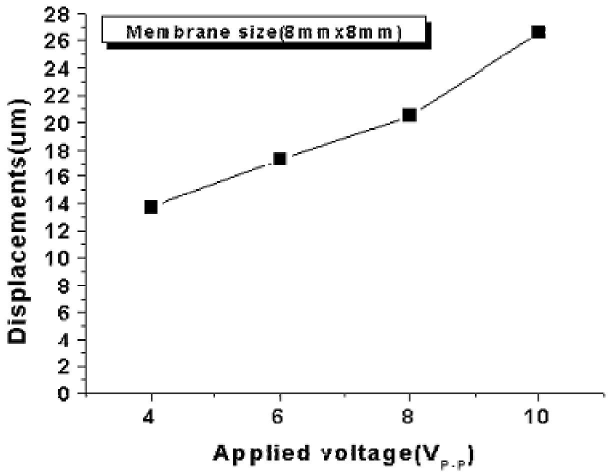


Fig. 7 A graph of displacement vs. applied voltage obtained from the fabricated 8 mm x 8 mm IPMC membrane actuator

2.4. Fabrication of IPMC micro pump using PDMS micro channel

One of micro pump elements is micro channel and it can be easily made with polydimethylsiloxane (PDMS). PDMS is widely used in microfluidics research because it is very easy to mold to fabricate microfluidic components such as channel and chamber. PDMS is also cheap compared to other material (silicon, glass, etc.) used in macro structure fabrication and the molding takes rather short time. In addition, PDMS is considered to be inert to various chemicals and it can be used in optical detection method through the PDMS since it is transparent to most wavelengths. Its adhesion to silicon, silicon dioxide, or glass is very good and the adhesion is fairly tight. Because the above merits, the PDMS was used in making micro channels for the micro pump. The PDMS channels consist of inlet, outlet, and pumping chamber, and micro channel between them. The fluid enters into the inlet, flows through the channel, arrives in the pump chamber, again flows through the channel, and exits out of the outlet. The micro channel doesn't have a simple channel with identical channel widths but have nozzle/diffuser structure at the connection between the channel and the pump chamber, as shown in Fig. 8, so that the flow would have a directional flow without valves when the chamber pressure is changed. A nozzle/diffuser structure enables the a directional flow without any valve when the chamber pressure increases and decreases by moving the pump membrane up and down because this structure makes the difference between the incoming flow and outgoing flow.

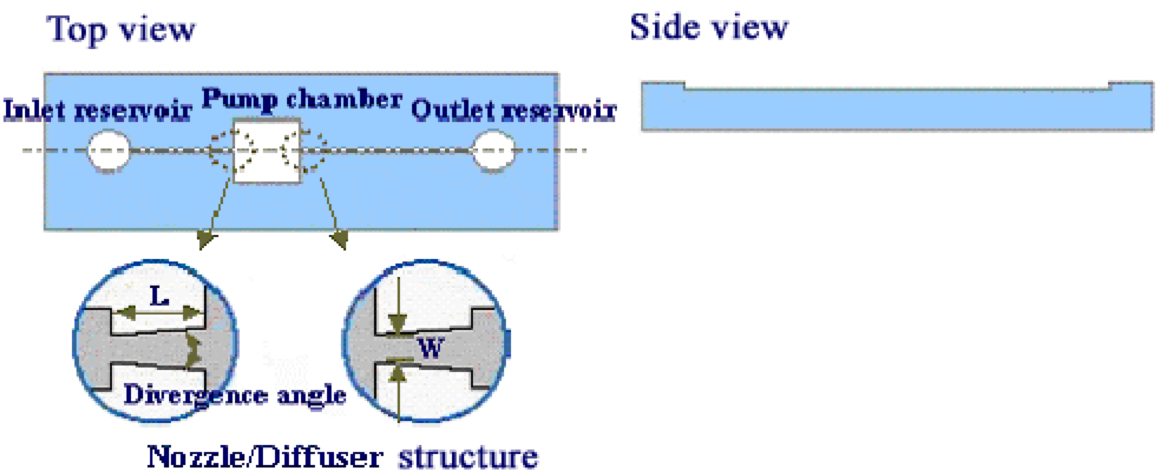
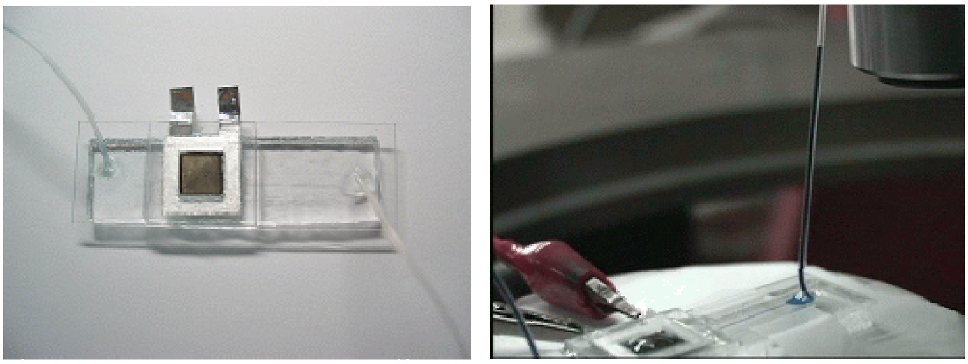


Fig. 8 A schematic picture of PDMS channel that was integrated with IPMC micro pump.

An IPMC micro pump has been fabricated by assembling the fabricated PDMS micro channel and the IPMC membrane-type actuator attached to a micro pump structure. The pump structure was made of acryl plate instead of silicon wafers for the convenience of handling and electrical connection. IPMC membrane actuator was assembled with a bigger acryl plate so that the top part of the IPMC actuator can be perfectly sealed when the IPMC actuator is bonded with the PDMS channel. Fig. 9(a) shows a picture of the fabricated IPMC micro pump and Fig 9(b) shows a picture of the fabricated micro pump while is tested for its functionality. Its pumping flow was measured using the set-up shown in Fig. 10 and the output flow characteristics measured from the fabricated IPMC micro pump were shown in Fig. 11.



(a) (b)

Fig. 9 (a) A picture of the fabricated IPMC micro pump. (b) A picture of the IPMC under testing.

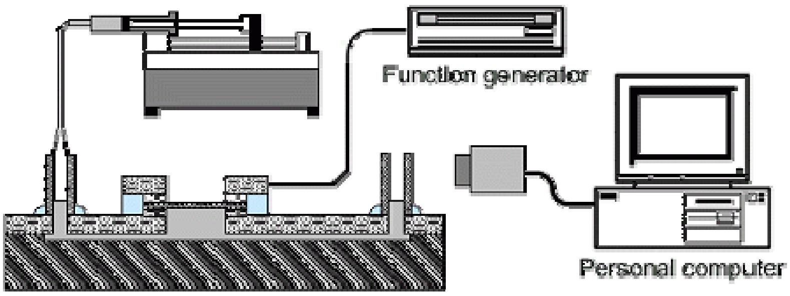
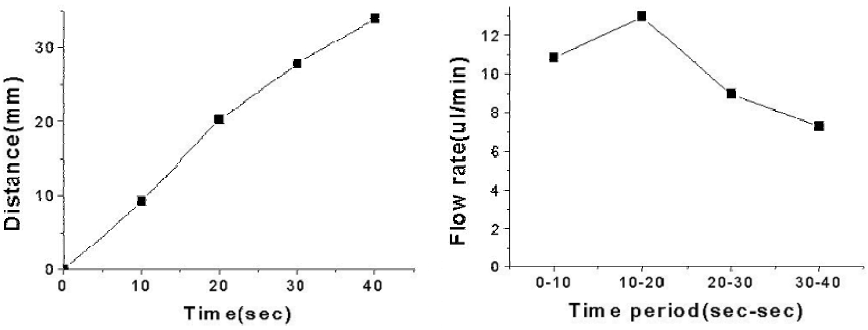


Fig. 10 A schematic picture of the measurement set-up for measuring IPMC micro pump function.



(a) (b)

Fig. 10 (a) Measured flow vs. the voltage application time. (b) Measured flow rate vs. measurement time duration.

3. CONCLUSION

It was demonstrated that ionic polymer-metal composite (IPMC) can be fabricated as a membrane-type actuator and it has enough force to pumping a small fluid our of a micro chamber and hence it can be used as an actuating membrane in a micro pump. The IPMC membrane-type actuator can be either by using a commercially available Nafion® 112 or thick Nafion® 117 while casting process would be very useful when it is necessary to fabricate IPMC membrane actuator with a micro pump structure in one fabrication process. After fabricating two 8㎜×8㎜ IPMC membrane-shaped actuators using a Nafion® 112 film, their displacements were measured before assembling them for making a micropump. The fabricated IPMC membrane-shaped micro-actuators showed displacement of 14～27㎛ at the applied voltage ranging from $4V_{P-P}$ to $10V_{P-P}$ at 0.5Hz. Displacement of the IPMC actuator fabricated with a commercially available Nafion is large enough to make the IPMC actuator be used as a membrane-shaped micro-actuator for functioning an IPMC micro-pump. IPMC micro-pump was fabricated by assembling IPMC membrane-shaped micro-actuator and PDMS(polydimethylsiloxane) micro-channel together. PDMS micro-channel was designed to have nozzle/diffuser structures. Nozzle/diffuser structures make the fluids flow from inlet to outlet when the IPMC membrane-shaped micro-actuator is deflected up and down by the applied voltage. The measured flow rate of the fabricated IPMC micro-pump is about 9.97㎕/min at 0.5Hz when the input voltage and duty ratio are $8V_{P-P}$ and 50%, respectively. The test results illustrate that the fabricated IPMC micro-pump is suitable for pumping fluid through micro-channel on a PDMS substrate. . One of the biggest obstacles in developing IPMC micro pump is its hermetic sealing between IPMC membrane and the pump structure.

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