Sensors and Actuators B 237 (2016) 660–665

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Fabrication of a diaphragm micropump system utilizing the ionomer-based polymer actuator

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 17 June 2016
Accepted 27 June 2016
Available online 28 June 2016

Keywords:
Nafion
Electroless plating
Diaphragm pump
Ionomer

ABSTRACT

This paper introduces an easy method for the fabrication of a diaphragm micropump using an ionomer-based polymer actuator. The polymer actuator was fabricated by electroless plating of platinum onto a Nafion-117 film. The electrode that serves as the diaphragm has a simple circular shape without any modification of the electrode surface and was punched from the polymer actuator film in a single step. The whole body of the micropump was designed to be the size of a credit card and was fabricated by the lamination of 13 layers to construct a three-dimensional flow path inside the body. The actuator assembly was embedded at the bottom of the pump to facilitate the exchange of the diaphragm. A square polarization waveform with amplitudes of +2.0 V and −2.0 V was applied to the pump, and the diaphragm micropump transported water at ~5 μL/s with no water leakage. The results presented in this work are an important demonstration that a diaphragm micropump can be easily fabricated for many micro-total analysis system (micro-TAS) applications using the nature of an ionomer-based polymer actuator as a flexible and large deformation available property in aqueous media.

1. Introduction

Over the last few decades, micropumps [1] have received much attention in the fields of micro total analysis systems [2–4], drug delivery [5], biological [1] and chemical analysis [6–9], microelectronics cooling [10], and space exploration [11]. In particular, miniature systems for chemical and biological analysis have been the focus of extensive research aimed at the development of standalone systems. Such systems have the advantages of consuming small amounts of reagents and requiring small amounts of samples; consequently, these systems can be used as portable systems for transporting fluids. The actuation mechanisms, fabrication methods, and applications for micropumps have been examined and developed [1,6–9].

Micropumps can be classified into displacement pumps and dynamic pumps. A related classification is mechanical pumps vs. non-mechanical pumps, depending on whether the pumping mechanism requires moving parts. One common method of constructing mechanical pumps is to use a diaphragm, and the mechanism by which diaphragm pumps operate makes them easier to fabricate. Therefore, researchers have used various material to develop a number of mechanical micropumps that operate on various mechanisms, including piezoelectric [12], electrostatic [13], thermopneumatic [14,15], electromagnetic [16], bimetallic [17], shape–memory–alloy actuation [18], and polymer-based actuation [19] mechanisms.

In the case of diaphragm pumps, the pressure forces are exerted through moving boundaries. That is, a membrane-displacement mechanism functions on the principle of an oscillating membrane creating an increase or decrease of the chamber volume. For example, fluid is drawn into the chamber through the inlet valves when the chamber volume increases. The fluid is forced out of the pump through the outlet when the volume decreases. A check valve is required to provide resistance between the inlet and the outlet to avoid regurgitation.

In the case of micropumps, although pumps that operate on the diaphragm mechanism are easier to fabricate, some such pumps require either high operating voltages (60–1000 V) because the high electric fields required to deform the piezoelectric and electrostatic actuators or high operating power to induce thermopneumatic or electromagnetic actuations [20]. These are serious drawbacks with respect to the practical application of portable embedded medical devices, remote environmental monitoring systems, and portable chemical analyzers, where both low- voltage and low-power operation are required.

Ionomer-based polymer actuators have attracted extensive attention as an artificial muscle that can undergo a bending motion

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http://dx.doi.org/10.1016/j.snb.2016.06.153
0925-4005/

similar to the motion of biological systems [25–33]. As previously discussed, the features of ionomer-based polymer actuators include operation at lower, safe potentials, a larger available range of deformation, the ability to generate force several hundred times greater than the actuator's weight, the ability to work under open-air conditions, and silent operation [31–35]. The bending principle of the polymer actuator developed in this study is basically surface expansion of a cathode and contraction of an anode, where internal ions statically interact with the polarized electrode fields [25–33]. The performance of these polymer actuators is very interesting as a next-generation motion principle. Diaphragm pumps have been fabricated using polymer materials because they enable operation at low driving voltages (a few volts), provide a large amount of deformation (a few millimeters), and allow flexible operation. For example, Nguyen et al. [21] used a Nafion–Ag-powder-based polymer actuator to fabricate a micropump. They used poly(dimethylsiloxane) (PDMS) for a flip valve and proposed both a characteristic electrode pattern and a flexible support to move the membrane. Fang et al. [22] used a polyvinylidene difluoride trifluoroethylene–polypyrrole-based polymer actuator to fabricate a pump with PDMS as a check valve. They notched the polymer membrane to promote displacement. Santos at al. [23] used a Nafion–Pt-based polymer actuator to fabricate a pump with a nozzle diffuser as a valveless system. Pt was plated in a characteristic shape onto the Nafion film. In many reported cases, although a simpler design should make pump fabrication easy, it can be noted that the electrodes proposed for such diaphragm units had complex shapes. A complex design of the electrode complicates the fabrication of the pump. The diaphragm displacement of the polymer actuator would be attenuated if all edges of the actuator film are clamped [24]. However, our experimental findings concerning ionomer actuators [31–35] suggest that an easier fabrication method wherein all edges of the actuator film of a simple circular shape are fixed is possible, even at the expense of performance. This possibility should be experimentally examined as an example of an easy fabrication method because such a method would introduce the possibility of using ionomer-based polymer actuators to develop diaphragm micropumps for micro-TAS applications, especially applications in aqueous media, i.e., the amount of displacement of the ionomer (Nafion)-based polymer actuator is dramatically increased under high-humidity conditions [31–33]. As long as the liquid medium in the micropump is aqueous, the polymer film will maintain a high moisture level, thereby maintaining a low stiffness of the film and enhancing the amount of displacement of the polymer actuator. On the basis of the numerous experimental findings related to ionomer-based actuators [31–35], we note that the actuator should work in a simple circular shape with no modification of the electrode surface to function as a good diaphragm membrane in aqueous media at lower working voltages.

Thus, in this paper, we propose an easy method for fabricating a diaphragm pump in which the electrode unit is an ionomer-based polymer actuator with a simple circular shape. Such a simple electrode can be easily punched from the polymer actuator film in a single step. The fabrication method here is substantially simpler than any previously reported method of fabricating a diaphragm pump with an ionomer-based polymer actuator. We are interested in a disposable micropump system with a flexible design for a micro-TAS for drug delivery and chemical analysis in aqueous media. Our experimental results and test observations confirm that our proposed ionomer-based micropump can produce a substantial flow rate. Although there is scope for improvement in our design, we believe that our results advance the viability of ionomer-based polymer actuators in micropump systems. Thus, this paper makes two contributions: the first is the experimental testing of a diaphragm film with the simplest circular shape without any modified patterns on the electrode surface. The movement of the diaphragm is achieved through the expansion and contraction via the characteristic property of ion transport and the membrane of the ionomer-based actuator. The second contribution is the introduction of an innovative and flexible layered structure for the fabrication of the micropump, where the layer of the check valve of the silicone rubber is also sandwiched within the unit and provides a good water-sealing structure. The pattern with the layers can be easily changed to create various flow paths of the micropump with no water leakage.

2. Experimental

2.1. Materials

Nafion-117 (eq. wt. 1100; thickness: ~180 μm), sodium borohydride (>98%), and $[Pt(NH_3)_4]Cl_2$ (tetraamineplatinum(II) chloride, >98%) were purchased from Sigma–Aldrich and were used as received. Nitric acid (conc. 70%) and lithium hydroxide monohydrate (>98%) were purchased from Wako Pure Chemical Industries, Ltd.; 18 MΩ cm water from a Millipore purification system was used for all experiments unless otherwise noted.

2.2. Fabrication of the polymer actuator

Perfluorocarbon sulfonate (Nafion-117, DuPont) was used as the polyelectrolyte film to fabricate the polymer actuator. A Pt layer was plated onto the Nafion film as the conducting layer. For the fabrication of the actuator, the polyelectrolyte film was first immersed in boiling nitric acid for 1 h to clean both the surface and interior of the film. This process removed organic contaminants from the film. The film was then washed and rinsed with deionized water and subsequently boiled in water for 30 min to ensure complete hydration. Next, the film was soaked in a 10-mM tetraammineplatinum(II) chloride solution at 25 °C. The film was then rinsed with water and transferred to freshly prepared 100-mM sodium borohydride for 2 h to plate the Pt. The film was rinsed with water, immersed in a diluted nitric acid solution, and again washed with water. Finally, the film was soaked in a lithium hydroxide solution and rinsed well with water to induce counter-cation exchange with Li^+.

2.3. Materials for the fabrication of the micropumps

The film of the Nafion-based polymer actuator was punched to make a circular diaphragm with a diameter of 22 mm. We fabricated flap valves by laser cutting from a silicone rubber sheet (thickness: 0.5 mm; MISUMI Co., Ltd., Tokyo, Japan). Two gaskets for embedding the actuator assembly were made from a nitrile rubber sheet (thickness: 0.5 mm; MISUMI Co.).

A three-dimensional flow path was fabricated by the lamination of clear acrylic plate (thickness: 1 mm and 8 mm; COMOGLASS, Kuraray Co., Ltd., Tokyo, Japan). The thickness of each layer was 1 mm, except for the 8-mm water reservoir layer. Each plate was adhered by light-curing adhesive (CLEARLUCE MA21, MS-ADELL Co., Ltd., Tokyo, Japan). The visible-light fluorescent lamp used for curing was a FL-V45 (MS-ADELL Co., Ltd., Tokyo, Japan).

3. Results and discussion

3.1. Fabrication of the actuator

We fabricated the polymer actuator by electroless plating of platinum onto the Nafion-117 (see Fig. 1A). The fabrication of the Nafion-based actuators comprises three basic stages: (a) the ion exchange of protons in the film for $[Pt(NH_3)_4]^{2+}$ cations, (b) chem-