MEMS-Fabricated ICPF Grippers for Aqueous Applications

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ABSTRACT

This paper presents the results of our ongoing investigation of using Nafion solution to construct micron scale actuators as grippers for underwater manipulation. We have demonstrated MEMS-based fabrication of cantilever structures composed of Au/Nafion/Au film layers on silicon substrates is possible. The smallest actuators fabricated were 30μm wide, 300μm long and 0.4μm thick. We have shown that 2-finger actuators (each 100μm wide, 1200μm long and 0.4μm thick) could be fully actuated in water at ~7V DC. In addition, we have found that micro Au/Nafion/Au cantilevers can respond to pH level changes in a solution environment, suggesting that they could potentially be used as biological sensors.

INTRODUCTION

Micromanipulation of biological entities is one of the most exciting ongoing research areas in Bio-MEMS. One of its goals is to find an improved technology to replace the current cell positioning and injection method, i.e., the use of pipettes to hold cells during the microinjection of chemicals or DNAs into cells. The major problem of the current technology is that, since the pipette suction force cannot be well controlled by hydrodynamic pressure, excessive suction force may often break the cell membranes. The pipette technology also cannot be used to rotate a cell during the microinjection process, which is a function that is highly desired in that the route of the injection may determine the localization of the injected matters (such as RNA) and subsequent response of cells [1]. Hence, this conventional technique of cell manipulation is rigid, imprecise, and invasive.

The deficiencies of the pipette technology have spawned much interest in using robotic means to grasp and manipulate biological cells. Reported microactuators targeting eventual robotic manipulation of biological cells are diversified. The first demonstration is an overhanging electrostatic gripper made by surface-micromachined polysilicon to grab a dry cell in 1992 by C. J. Kim et al. [2]. However, MEMS electrostatic actuators typically require higher actuation voltage and have small displacements, and hence are not suitable for operations in biological fluids (bubble generation by electrolysis will occur at ~2V potential in water). For a more comprehensive discussion on the limitations of conventional MEMS actuators operating in aqueous environments, [3] can be referenced.

In recent years, novel materials, mostly belonging to the electroactive polymers categories such as Nafion-based Ionic Conducting Polymer Films (ICPF), polypyrrole of conjugated polymers, and PANI of conductive polymers, were investigated by researchers as possible materials for artificial muscles (see [4] for example). As the development of these materials becomes more matured, they offer the potential to break some of the limitations that are set by current MEMS thin film materials such as polysilicon, SiO_2, Si_3N_4, and metals in engineering micro sensors and actuators. Smela et al. (1999) [5] and E. W. H. Jager et al. (2000) [6] have already developed fabrication processes for conjugated polymers and demonstrated micro-robotic appendages capable of manipulating micro objects in aqueous environments. Nevertheless, their actuators have slow response and were limited to operations in electrolyte solutions, which may not be suitable for the survival of many biological entities.

Our ongoing work is to investigate the possibility of using ionic conduction polymer to develop Ionic Conduction Polymer Films (ICPF) micro actuators. These flexible materials convert electrical energy into mechanical energy effectively. Under an electric field, ions move in and out of the conducting polymers, which lead to simultaneous changes in volume as well as variations in physical properties. These polymers are undergoing intense analyses and improvements by the artificial muscles community (for example see [4] and [7]). However, to the best of our knowledge, work reported thus far only focus on meso and macro scale actuators, and no existing data are available for Nafion based actuators with dimensions less than 1mm in length except from our group.

In this paper, we will present our work on the fabrication of Nafion-based microactuators using MEMS related processes and some initial experimental results in using them as actuators and sensors in aqueous environment. Our goal is to find how well does

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the ionic conduction mechanism scale with size, i.e., if the relative large force to input voltage ratio and fast frequency response of ICPF actuation characteristics can be preserved at micro scale, then these actuators will find many new applications in the bio-manipulation area not accessible by existing MEMS actuators.

MICRO FABRICATION OF NAFION ACUATORS

A. Fabrication by Laser-micromachining

Most of the reported ICPF actuators were developed using commercial Nafion™ membranes with standard thickness of 200 m. This film thickness restricts the allowable deflection of ICPF actuators when they are scaled down in length and width. In our previous work, ICPF actuators made from commercial Nafion 117 membrane were successfully fabricated using a Nd:YAG laser system [8]. Actuators with dimensions of w=300 m, l=3000 m, t=200 m were actuated under water with 15V DC voltage. Incidentally, an actuator of these dimensions is considered as a "microactuator" by traditional robotics community, but it is considered as a "meso-scale" actuator by MEMS researchers. We performed parametric experiments to understand the behavior of those Nafion actuators with variations of applied voltage and actuator geometries, and found that to achieve grasping motion (i.e., closing the fingers of a gripper) more than 15V of applied voltage was necessary because a large energy was need to overcome the structural rigidity of the Nafion films.

B. Fabrication by MEMS-based Process

Commercial Nafion solution from Dupont (SE-5012) was used to fabricate the ICPF micro actuators in the current study. The actuators were made of Au/Nafion/Au layers with the Nafion film thickness controlled by spin-on process. Several designs of ICPF actuators were batch fabricated on a 4-inch silicon wafer using surface micromachining technology. The process flow is shown in Figure 1. The fabrication started with thermal oxidization of a SiO_2 layer (~0.5 m) on the silicon substrate, followed by the deposition of ~1 m thick aluminum layer. The aluminum layer served as the sacrificial layer for the actuator cantilever structures. The first gold layer (~0.1 m) which was used as the bottom electrode was sputtered on and patterned by lift off. Afterwards, Nafion solution was spun-on and cured by baking on a hotplate at ~70°C for 5~8 minutes and ~150°C for 5~8 minutes (similar to the recasting process reported by T. Arimura [9]). The relationship of the film thickness and the spinning rate is also shown in Figure 1. It was possible to increase the Nafion thickness by repeating the spinning and heat-curing procedures. However, as number of layers are increased, residual thermal stress may cause cracking of the Nafion film. In order to generate a relatively uniform thin film, we used ~0.2 m thick Nafion in our process. Then, ~0.1 m thick gold layer was sputtered on top of the Nafion as the top electrode for the ICPF actuators. Finally, the sacrificial aluminum layer was removed by phosphoric acid to release the structures.

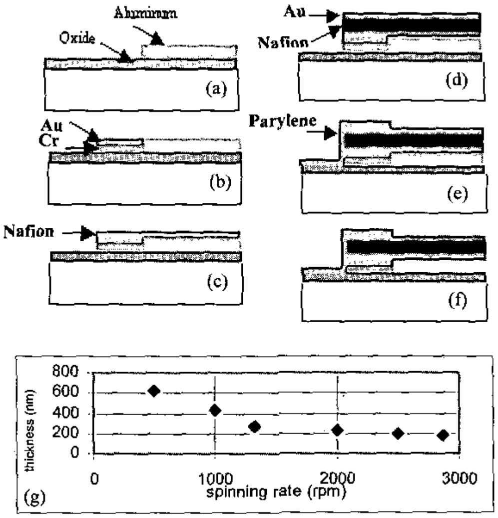

Figure 1. Nafion actuator fabrication process flow. (a) Deposition and patterning of sacrificial aluminum on oxidized Si. (b) Deposition and etching of adhesive chromium layer. Parylene coated and patterned. (c) Deposition and liftoff of bottom gold layer. (d) Spin-on Nafion. Deposition and etching of top gold layer. Etching of Nafion by plasma. (e) Parylene layer coated and patterned. (f) Removal of sacrificial layer. (g) Relationship between the spin-on Nafion thickness and the spin rate.

Our experimental results showed that the release procedure played a key role in producing the final structures, i.e., the sacrificially released actuators had different released-configurations depending on the release process. For instance, we used phosphoric acid without dilution and heated it to ~40°C to sacrificially etch Al (etch rate ~100Å/min). The samples were taken from the acid solution and immersed into DI water to inspect the progress of the release occasionally. After about 2 hours with several immersions into DI water, the cantilevers laid horizontally in acid as shown in Figure 2(a). When DI water was added into the acid, the cantilevers curled up as the microscope picture shows in Figure 2(b). If sufficient water was added, it completely curled up instantaneously as shown in Figure 2(c). However, this phenomenon did not occur when the samples were released in phosphoric acid for several hours without occasional submersion in water at room temperature. In this case, the resultant cantilevers remained horizontal as shown in Figure 2(a). These cantilevers were used to do the electrical actuation test

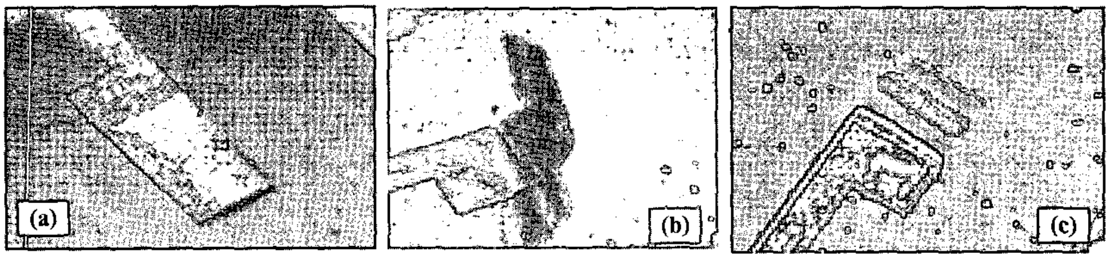

Figure 2. (a) A released actuator in phosphoric acid. (b) When DI water was added to acid, the actuator begun to curl. (c) If sufficient DI water was added, the actuator completely curled up. The actuators were released in phosphoric acid with occasional immersion in water at room temperature. The dimensions of the Nafion layer in the actuator shown above are w=200 m, l=500 m, t=0.2 m.

described in the Experimental Results section. The smallest actuators fabricated were 30 m wide, 300 m long and 0.4 m thick (including the metal electrodes). The exact mechanism of the curling behavior is being studied but possible causes were suggested in [3]. The above behavior suggests that with proper process steps, Nafion structures can be used as a pH sensor.

In addition, the thickness difference between the top and bottom electrodes also determined the shape of the structure after release - an indication that it is very important to keep the residual stresses in both the Nafion and metal films under control during the fabrication process (refer to Figure 3).

EXPERIMENTAL RERSULTS

The testing of the polymer actuators was carried out using a micro probe station. The samples were placed in a Petri dish filled with DI water. Voltage was applied to the samples through two micro probes. The resultant deflection was captured through a microscope with a CCD camera linked to a computer terminal.

A sequence of motion of a 2-finger actuator actuated in DI water is shown in Figure 4 (2-D top-view under microscope). The actuator (each finger w=100 m, l=1200 m, t=0.4 m) started to deflect at ~5V. It reached full deflection, i.e., 90° change of tip direction when the voltage was ~7V. Gas bubbles due to electrolysis were generated from both electrodes. After the voltage was removed, the beams returned to their original positions. In order to understand the electromechanical property of the ICPF microactuators, the current-voltage property of some actuators were measured. I-V curve of a typical actuator is plotted in Figure 5 with the current measured at linearly increased DC voltage (data from a single finger structure with w=300 m, l=1200 m, and t=0.4 m). The maximum power consumption of the actuator was estimated to be 0.054mW from the plot. When the voltage goes higher than ~5V, the current almost disappears, which seems to indicate an ionic deficiency in the sandwich structure. Detail calibration is ongoing and will be reported later.

DISCUSSION

The estimated actuation force of the underwater actuators is discussed in this section. Calibration of gripping force and lifting force of these polymer actuators is difficult by conventional techniques since these actuators have large deflections and work under water. Eventually, different dimensions of silicon blocks will be fabricated to calibrate the force output of the actuators. However, the minimum force output of an actuator must exceed the sum of the fluid drag, gravitational and spring-restoring forces in order for it to actuate and grip a cell (Figure 6). Note that in a liquid medium, capillary force between the actuator and the substrate is not a concern because of the absence of air-water interface as in the case for actuation in air.

Fluid Drag Force - The Reynolds Number estimated for actuators of this dimension moving in water is <1 (refer to [10] for more elaborate analysis), so the flow around a moving actuator is laminar, and hence we can assume the skin friction is negligible, and the only source of drag force is pressure drag. Then, assuming the worst case scenario where a 1D uniform free-stream flow impinging on a stationary plate, the drag force F_p can be calculated using Bernoulli's Equation:

$$F_P = \rho U^2 A/2 \qquad (1)$$

where A=wl, (w is the width and l the length of the actuator) which is the area impinging on the flow, ρ is density of water, and U is the average actuator velocity. To estimate the velocity of the actuator we assumed that for a 1.2mm x 100 m x 0.4 m actuator (same as the one shown in Figure 4), the tip reached 30° within 1 sec (from experiment). Then, referring to Figure 6, the average velocity U is ~0.5mm/sec. Hence, F_p ~0.015nN.

Weight of the actuator - The weight of the actuator body F_m is mainly that of the gold film (0.2 m). Hence, F_m~ρbLt=4.6nN, where ρ is the density of gold (13.6kg/m^3), and w, l, and t are the actuator parameters as defined earlier.

Force to bend the actuator - Using linear bending beam theory, the actuation force required to deform a beam with a spring constant $k=3EI/l^3$ by a distance y is approximated by $F_k=Ky$. So, F_k is ~ 32nN when y is ~0.5mm at tip deflection of 30° and F_k is ~ 0.6nN when y is ~10 m (EI is calculated based on a tri-layer structure).

Therefore, the total minimum force output for a 1.2mm x 100 m x 0.4 m actuator is $F_m+F_p+F_k$ and is ~36.6nN to reach tip deflection of 30° based on the above analyses. The main energy consumption is to overcome the spring-restoring force of the actuator.

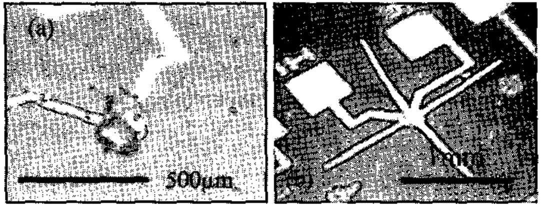

Figure 3. Micro 4-finger actuators with different configurations in different batches after the release process. The dimensions of Nafion layer in each finger of the actuators are w=30 m, l=300 m, and t=0.2 m in (a), and w=30 m, l=1000 m, and t=0.2 m in (b).

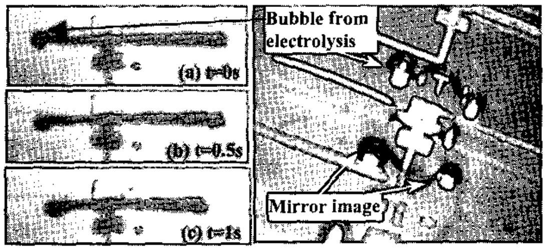

Figure 4. A micro Nafion actuator under 5V and 7V DC voltage input. (a), (b),(c) are 2-D top views under 5V. (d) is a 3-D picture of actuator under 7V to reach full closure of gripper. The bubbles were caused by electrolysis of the aqueous medium.

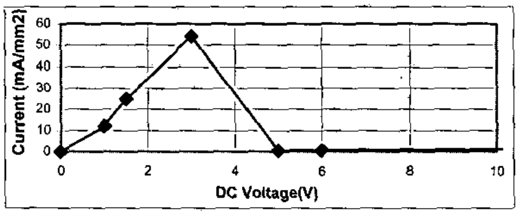

Figure 5. I-V curve of a single finger actuator (w=300 m, l=1200 m, and t=0.4 m). Current was measured when DC voltage was linearly increased.

CONCLUSIONS

Novel ICPF micro actuators were successfully fabricated on silicon substrates. We have demonstrated that these actuators can operate in an aqueous environment and can be potentially used for manipulation of micro objects in aqueous solutions. However, electrolysis was observed during actuation in DI water. The performance of the actuators is being studied to realize precise control of their actuation behavior.

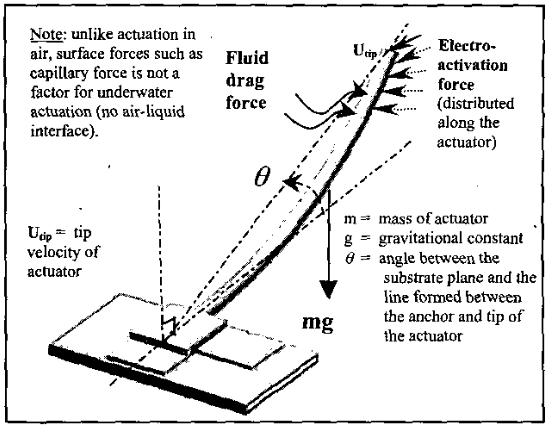

Figure 6. Illustration showing various forces acting on an actuator.

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