ELECTROLYSIS-BASED INCHWORM ACTUATORS

L. Giacchino*, Y.C. Tai

California Institute of Technology, Pasadena, California, USA

ABSTRACT

We have designed, fabricated and tested an inchworm actuator using water electrolysis as the mechanical power source. To facilitate the inchworm mechanism, each actuator is made of two sealed silicone balloons. When electrolysis is run inside a balloon, the balloon expands due to gas generation. When electrolysis is stopped, the balloon shrinks due to gas recombination and permeation through the silicone. Bidirectional movement of a rotor, e.g., a metal probe, is obtained by applying specific expansion/shrinkage sequences to the balloons. The device works at low voltage and current, with peak power consumption around 100 μ W. Displacement of silicon and metal probes from 20 μ m to 75 μ m per cycle was demonstrated. Also reported here is a new hydrogel-enabled balloon fabrication process.

INTRODUCTION

Electrolysis Actuation

Electrolysis of water has been successfully employed in a number of MEMS devices, even though it is not as common as more traditional actuation principles (such as electrostatic or piezoelectric). The actuation mechanism is based on the volume expansion of hydrogen and oxygen gases generated by the electrolysis of water on the surface of two electrodes. The well known electrochemical reaction is (if protons are assumed to transport the charge)

The conversion of water from liquid to gas can produce a significant displacement if volume expansion is allowed at low pressure, or it can produce a high pressure (hence a large force) in case of constrained volume. Electrolysis can also operate at a relatively low voltage and power. Electrolysis actuation has been previously employed in microdevices such as micropumps [3] and microfluidic valves [4]. Our group has already demonstrated the basic electrolysis balloon based on water electrolysis [1,2]. This work is to demonstrate an inchworm actuator to move a metal neural probe using two electrolysis balloons.

Movable Neural Probes

Over decades of cortical neural prosthesis, it is found that a “movable” neural probe [5] that can track or follow a neuron is highly desirable for long-term, reliable prosthesis. This is challenging, however, because the ideal movable probes should have the merits of low voltage, small power, bidirectional and latchable movement, large force (to penetrate the brain tissue), and large total traveling distance (i.e., ~mm). On the other hand, speed is not an important requirement because neuron movement is sporadic and slow. Therefore, electrolysis actuation embedded in an inchworm mechanism is an interesting candidate for this application.

DESIGN

Each inchworm stator is made of two balloon actuators. Detailed analysis and experimental results for balloon actuators were already reported in [1]. Each balloon is made of silicone with

two platinum electrodes and electrolyte inside. In our previous devices, however, balloons were fabricated with parylene. In the current design, parylene is replaced by silicone. There are two major improvements from using silicone over parylene. Silicone is more flexible (because of smaller elastic modulus) and much more permeable to gases and water. The higher permeability allows faster relaxation, which reduces the inchworm cycle time. Even though permeation causes a net loss of water from the balloon interior, osmosis is used to replenish water back into the balloon when immersed in aqueous environment. In the body, the device is in a saline solution; therefore, osmosis is available as a mechanism to replenish the balloons.

In our inchworm design, one balloon is used to clamp the probe horizontally; the other balloon is to provide vertical displacement. The metal probe rotor is placed between two discs, which clamp the probe from both sides when the clamping balloon expands. The inchworm movement is obtained by expanding and relaxing the balloons in a specific order, as illustrated in Fig. 1. The vertical displacement (i.e., up or down direction) can be reversed by modifying this order.

Figure 1: Inchworm principle. The first row illustrates forward displacement (downward in the figure), while the second row illustrates backward displacement (upward in the figure). For forward displacement, the probe is first clamped, and then the inchworm is moved down. For backward displacement, the inchworm is first moved down, and then the probe is clamped. The probe is moved backwards during the relaxation of the inchworm.

The inchworm mechanism can provide variable displacement per cycle, depending on the expansion of the displacing balloon. The system does not impose a minimum step, which is determined by the accuracy of actuation of the displacing balloon. Large traveling distance can be obtained in multiple cycles, and the constraints are the probe length and the amount of water in the balloons.

The inchworm design has three advantages. First, the inchworm is able to provide large displacement in multiple cycles. Second, the inchworm is inherently latchable. Third, the inchworm decouples the fabrication of the actuator from that of the probe, and it is, therefore, able to be adapted to various probes.

The position of the spring on the frame was chosen to create a lever effect. As shown in Fig. 1, the displacing balloon is connected to a point close to the spring. Due to the distance between this point and the probe, the displacement applied by the balloon is amplified at the probe. This is confirmed by a finite-element simulation. The lever design, however, causes the

Figure 2: Fabrication of the inchworm. First the silicon frame and discs are fabricated. Then the discs are assembled onto the frame. Balloons can have either one or two discs at the sides (the figure shows the process in both cases). In the final step, laser ablation is used to release the moving side of the clamping balloon.

inchworm arm and the probe to move along a curved path during actuation. This is particularly noticeable for large displacement in a single cycle. Placing the spring in-line with the displacing balloon would allow the probe to move along a straight line, but it would not provide any displacement amplification.

FABRICATION

Silicon Frame and Ruler Probe

The main component of the inchworm is a silicon frame. The frame provides a spring mechanism, and it supports the platinum electrodes needed for electrolysis. The fabrication steps are illustrated in the first row of Fig. 2. A picture of a fabricated frame is shown in Fig. 3a. The fabrication starts with a 200 μm thick silicon wafer. The wafer is coated with 0.5 μm of Parylene C (Specialty Coating Systems), which is then melted at 350 $^{\circ}\text{C}$ in N_2 atmosphere. This molten layer is used as an adhesion layer for a subsequent 2 μm Parylene C deposition. Platinum is then deposited by e-beam evaporation and patterned with a lift-off process. Another layer of Parylene C is deposited, thus completing the insulation of the metal traces. Pads and electrodes are opened in the top parylene layer by reactive ion etching (RIE) using O_2 plasma. To release the devices, parylene is completely removed by O_2 RIE around the outline of the frames. The exposed silicon is then etched by deep reactive ion etching (DRIE) to define and release the frames.

Silicon probes with a ruler pattern on the top surface are fabricated on the same wafer as the silicon frames (see Fig. 3d). The ruler pattern is obtained on the platinum layer. The pattern is convenient to measure the displacement of the probe. In some experiments, a commercial metal neural probe is mounted on top of the ruler probe, which then acts as a shuttle for the metal probe (see Fig. 7). Mounting a commercial probe on the silicon probe makes it possible to use different kinds of neural probes (with different width) without redesigning the inchworm clamp.

Figure 3: Fabricated components. a) Silicon frame. b) Clamping disc. c) Balloon disc. Discs of different sizes are fabricated. The marks on the discs indicate the diameter and the size of the central opening. d) Ruler probe. The spacing between the large numbers is 1 mm, for a total length of 9 mm.

Silicon Discs

Special silicon discs are used to better define the balloon shape (balloon discs) and to create the probe-clamping mechanism (clamping discs). The two types of disc are fabricated with the same process. The balloon discs provide anchor trenches for silicone to improve the balloon sealing. There are two circular anchor trenches on the front side of the disc and trenches all around the disc sidewall.

The fabrication process of the discs is illustrated in the second row of Fig. 2. A 1.5 μm thick layer of silicon dioxide is grown on thin wafers (200 μm thick) by wet oxidation at 1050 $^{\circ}\text{C}$. The oxide is then patterned and used as a mask for DRIE. Two kinds of trenches are needed: anchor trenches (5 μm wide) and release trenches (100 μm wide). The DRIE etching rate is lower in narrower trenches (DRIE lag), making it possible to obtain both types of trench with a single-mask process. When the release trenches are etched all the way through the wafer (thus releasing

the discs from the wafer), the anchor trenches are only about 80-90% through. Pictures of the fabricated discs are shown in Fig. 3b and Fig. 3c.

Balloons

For support during assembly and balloon fabrication, the silicon frame is glued to the edge of a glass slide. The silicon discs (balloon and clamping discs) are then assembled onto the frame using an xyz micrometer stage equipped with tweezers. The discs are secured to the frame using biocompatible epoxy (Epoxy Technology, EPO-TEK 301-2), which also seals the frame-disc interface. Balloons can be fabricated with either one or two discs, as shown in the third and fourth row of Fig. 2. A silicon frame with assembled balloon discs is shown in Fig. 4a.

Hydrogel (i.e., sodium polyacrylate) is then dispensed on the balloon discs. Alternatively, hydrogel can be dispensed on the discs before assembly. Water is dispensed on the hydrogel using a commercial fluid dispenser (EFD 2000XL) with a 33-gauge tip. When the hydrogel is made wet, it expands. Biocompatible silicone (Dow Corning MDX4-4210) is painted around the hydrogel and the discs using a thin wire. It is important to keep the hydrogel wet and expanded while silicone is cured because the hydrogel determines the balloon internal volume. For this purpose, the curing is done at 60 °C in a humid environment, so there is no net permeation of water from the hydrogel to the outside through the silicone. Raising the temperature over 60 °C causes some condensation on the silicone during the cure process, causing its surface to be hazy. When the silicone is cured, the device is immersed in water, and more water is driven into the balloon by osmosis.

This process is very convenient because no hole in the balloons is required to release any sacrificial material or to fill the balloon with electrolyte. The hydrogel provides the mechanical support for the silicone, and it stays inside the balloon in the finished device. Filling of the balloon is obtained by osmosis through the silicone membrane. This is very advantageous compared to our previous process [1]. The balloons were previously fabricated with sacrificial photoresist, which had to be released in acetone through a hole in the silicone membrane. The device was then filled through the same hole by immersing the device into an electrolyte solution in vacuum. The hole then had to be sealed by epoxy or silicone. The hole, even after sealing, represented a weak point and the most common cause of seal failure. The hydrogel process avoids the hole completely, thus improving the reliability of the device.

The last step in the inchworm fabrication is the release of the clamping balloon, as shown in the last row of Fig. 2. In order to provide the support necessary for fabrication, the front side of the clamping balloon is part of the silicon frame. The connection to the frame is removed by laser ablation of silicon. In this way, the clamping balloon is free to expand and clamp the probe.

Cable Connection

When the inchworm is operated in water (or saline in the body), the electrical connection to the pads must be isolated from the surrounding environment. A commercial flat cable with 0.5 mm pitch (Parlex Corp.) is electrically connected to the pads by conductive epoxy. This is done before the balloons are fabricated. The connections are then encapsulated into biocompatible epoxy and biocompatible silicone for insulation (see Fig. 5).

Figure 4: a) Silicon frame with assembled balloon discs (double-disc balloons case). b) Finished inchworm after release of the clamping balloon by laser ablation.

Figure 5: Finished inchworm with cable: a) in air, b) in water.

RESULTS

Standalone Balloons

Balloon actuators are the building blocks of the inchworm. For this reason standalone silicone balloons were first tested. Fig. 6 shows experimental results for the actuation and relaxation of a silicone balloon. The relaxation time is largely improved compared to parylene balloons due to the faster permeation of gases through silicone (from 20-30 minutes for a 10 μm thick parylene balloon to about one minute for a 100 μm thick silicone balloon). The displacement is measured by a linear variable differential transformer (LVDT). The LVDT is spring-loaded, with a spring constant of 2.5 $\text{mN}/\mu\text{m}$. The actuator has to overcome the spring force, which limits the achievable displacement. However, this shows that the balloon is able to generate force in the tens of mN. Without the LVDT, a single-cycle displacement in excess of 100 μm was demonstrated.

Figure 6: Expansion and relaxation of a standalone balloon. The displacement was measured with an LVDT (spring constant 2.5 $\text{mN}/\mu\text{m}$). Electrolysis was stopped at the dashed line. Silicone is about 100 μm thick. The model fits the experimental data closely.

Balloon Model

In [1] we illustrated a model for the balloon actuation. The model is able to keep track of the amount of H_2O , O_2 , H_2 and N_2 (from air) inside the balloon as a function of time. It is based on

mass balance equations for each component (n_x represents the moles of species x inside the balloon):

$$dn_{O_2}(t)/dt = g(t) - r(t) - c_{O_2}w\Delta p_{O_2}(t) \quad (2.a)$$

$$dn_{H_2}(t)/dt = 2g(t) - 2r(t) - c_{H_2}w\Delta p_{H_2}(t) \quad (2.b)$$

$$dn_{H_2O}(t)/dt = -2g(t) + 2r(t) - c_{H_2O}w\Delta\mu_{H_2O}(t) \quad (2.c)$$

$$dn_{N_2}(t)/dt = -c_{N_2}w\Delta p_{N_2}(t) \quad (2.d)$$

The model includes the effects of gas generation by electrolysis, $g(t)$, gas recombination, $r(t)$, and permeation through the balloon walls. The permeation flux for gas x is assumed proportional to the gas partial pressure gradient Δp_x across the membrane, where c_x is the permeation coefficient and w is the ratio of surface area and membrane thickness. Several improvements are introduced to the model in [1]. First, the treatment of water permeation is extended to also model osmosis. The amount and direction of water permeation is determined by the chemical potential gradient across the membrane $\Delta\mu$. Second, the balloon volume is not assumed to be constant, and balloon expansion as a function of internal pressure is included. This dependence is approximated by a linear relationship. Third, solubility of gases into water is included. The balloon internal volume is divided between a liquid and a gas phase. Due to solubility, O_2 , H_2 and N_2 are present both in the gas and in the liquid phase. The amount of each component in solution is assumed proportional to its partial pressure. Fig. 6 shows that the model fits the experimental data very closely.

Inchworm Actuators

The fabricated ruler probe is used to calibrate the inchworm. The displacement is read by observing the ruler pattern under a stereoscope. The experiments are video-recorded using an eyepiece camera. In some experiments, a commercial metal neural probe is also mounted onto the ruler probe (Fig. 7a). The inchworm is able to displace the probe in both directions, with a displacement per cycle between 20 μm and 75 μm (Fig. 7b). The applied voltage is typically 3.5 V, with a resulting current of 20-30 μA . Each cycle is completed in about 10 minutes. Experiments were run both in air and in water. The maximum number of cycles before a break for osmosis-refilling is needed is around 10. The refilling time ranges from a few hours to several days, depending on the amount of water consumed and the number of additional cycles desired.

When actuated in water, gas bubbles form on the balloon surface during actuation. This is due to gas permeating out of the balloon through the silicone. This gives a visual confirmation of the role of permeation for balloon relaxation.

The principal failure mode is the formation of a leak in the balloons. In some cases, the leak forms at the disc-frame interface, and it is probably due to the epoxy not completely filling the gap between the disc and the frame. This kind of leak is usually visible only when the balloon reaches a certain pressure, and it is typically small enough that the balloon can still be operated. In other cases, the leak forms at the edge of the disc due to stress concentration in the silicone. This can be prevented by making sure the silicone is thick enough around the edge of the disc. A leak of this kind is easily repaired by another application of silicone.

Figure 7: a) Complete inchworm system. A commercial metal probe is mounted on top of a silicon ruler probe. b1-b3) Close-ups of the probe, with frames showing the probe displacement (experiment run in air). b1) Initial position of the probe. b2) Probe after 4 cycles of forward displacement (cumulative displacement: about 100 μm). b3) Probe after 1 cycle of backward displacement from b2 position (displacement: about 75 μm).

CONCLUSIONS

Inchworm actuators based on two electrolysis-actuated silicone balloons were designed, fabricated and tested. Standalone silicone balloons were tested, and a model for their behavior was also developed. The inchworm was demonstrated to provide variable displacement per cycle (up to 75 μm per cycle), with the balloons generating forces in the mN range. The inchworm operates at low voltage (typically around 3.5 V) and low current (typically between 20 and 30 μA), and it completes one cycle in about 10 minutes. The inchworm was tested both in air and in water. Displacement of a silicon probe and a commercial metal neural probe was demonstrated and video-recorded.

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CONTACT

* L. Giacchino, tel: +1-626-395-5899; lucagi@caltech.edu