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Electrochemical membrane microactuator with a millisecond response time

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ABSTRACT

Lack of fast and strong actuators to drive microsystems is well recognized. Electrochemical actuators are considered attractive for many applications but they have long response time (minutes) due to slow gas termination. Here an electrochemical actuator is presented for which the response time can be as short as 1 ms. The alternating polarity water electrolysis is used to drive the device. In this process only nanobubbles are formed. The gas in nanobubbles can be terminated fast due to surface assisted reaction between hydrogen and oxygen that happens at room temperature. The working chamber of the actuator contains concentric titanium electrodes; it has a diameter of 500 μm and a height of 8 μm. The chamber is sealed by a polydimethylsiloxane (PDMS) membrane of 30 μm thick. The device is characterized by an interferometer and a fast camera. Cyclic operation at frequency up to 667 Hz with a stroke of about 30% of the chamber volume is demonstrated. The cycles repeat themselves with high precision providing the volume strokes in picoliter range. Controlled explosions in the chamber can push the membrane up to 90 μm.

1. Introduction

Miniaturization of different systems is a clear trend in the modern world. To drive any mechanical device one has to transform the driving energy (for example, energy of a battery) to mechanical movement. This role is played by actuators. The actuator is only a part of microsystems but it is a bulky part dissipating a large portion of the driving energy. In contrast with the macroscopic world, where we have got efficient and reliable motors such as electromagnetic motors or internal combustion engines, there is obvious lack of fast and strong autonomous microactuators. For example, microfluidic devices [1] that are designed for fast and cheap chemical, biological, or medical tests often rely on macroscopic compressors to pump liquid through microchannels. Fabrication of a small field coil to generate a significant magnetic field in the electromagnetic motors is not an easy task [2]. On the other hand, microengines using internal combustion [3] cannot be scaled down because combustion reactions quench in a small volume due to fast heat escape via the volume boundaries [4,5].

A great number of principles and techniques is used to build microactuators [6–8]. They include piezoelectric [9,10], electrostatic [11,12], thermal [13–15], electrokinetic [16,17] and many other actuation principles. Actuators using electrostatic forces are fast but they develop rather weak forces. On the contrary, the actuators using the thermal principle are slow but strong. Piezoelectric actuators are very popular, they are strong and fast but the main disadvantage is a small stroke per unit voltage. Due to this feature one has to apply a high voltage or has to increase the size of the actuator. For example, in a recent commercial product Insulin Nanopump™ developed by Debiotech a piezo actuator with a diameter of 5 mm is used, which is by far the largest element of the pump [18]. An additional problem is that the piezoelements are not well compatible with standard microfabrication technology.

A special class of actuators uses the electrochemical process such as water decomposition to produce mechanical work [19–26]. In these devices the gas generated by water electrolysis pushes a flexible membrane. The electrochemical actuation develops large driving force, provides accurate flow control, generates low heat, and is compatible with microtechnology. However, the electro-

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chemical actuation is notoriously slow because to return the actuator in the initial state one has to terminate all the produced gas. It can be done by natural dissolution of the gas in a large volume of liquid that takes a long time (5–10 min) [19,20], some authors using venting of the bubbles [23], but the most advanced way is to initiate the reverse reaction between the gases, for example, using catalytic properties of platinized electrodes [26]. In the latter case the response time is considerably reduced but stays in the range of 100 s.

Alternating polarity electrolysis performed by short (a few μs) voltage pulses [27] demonstrated unexpected properties that can be used as a new principle to build a fast electrochemical actuator [28]. If each electrode is kept equal time at positive and at negative potential and if the polarity changes with a frequency of the order of 100 kHz, only nanobubbles are generated by the process. Recently [29] the average size 80 ± 10 nm of these bubbles has been directly measured with the dynamic light scattering method. Production of a large amount of gas was proven by the change of the refractive index of liquid around the electrodes [27]. This amount can be so large that the optical image of the electrodes is distorted [30] but no light scattering on microscopic or larger bubbles is observed. The alternating polarity process builds up a significant pressure in a closed microchamber [28] but, again, no light scattering on microscopic bubbles were observed. The most peculiar feature of the process is that this pressure relaxes just in 100 μs after switching off the electrical pulses.

Fast termination of the gas is explained by combustion of hydrogen and oxygen in nanobubbles [27]. The reaction happens spontaneously at room temperature due to surface assisted processes that dominate in nanobubbles due to a large surface-to-volume ratio [31]. Although the details of the reaction mechanism are still not clear, one can use this reaction to reduce drastically the response time of the electrochemical actuators. In this paper we are going to show that this time can be reduced from minutes to 1 ms and, probably, this is not the ultimate limit.

The first practical application of the alternating polarity electrolysis for a valveless micropump was not very successful [32]. The pump demonstrated a low pumping rate of 0.15 nl/min at an operating frequency of 4 Hz. The reaction chamber of the device was made from polydimethylsiloxane (PDMS) that is too soft material: instead of pumping liquid the chamber is inflated in response to the pressure increase. Moreover, platinum electrodes were not able to support a high current density and destroyed fast.

A miropump of the same design works much better in a so called regime of exploding bubbles [33]. In this case the pumping rate was 12 nl/min at an operating frequency of 1 Hz that is not bad keeping in mind that the chamber volume (3.7 nl) is much smaller than in most of the micropumps. Fast video reviled the processes happening in the chamber during the pumping. For each cycle there is an incubation time needed to reach a critical density of nanobubbles inside of the chamber. When this critical concentration is reached the nanobubbles start to merge and form a microbubble containing stoichiometric mixture of H_2 and O_2. This mixture is ignited spontaneously and the bubble explodes. As the result just in 100 μs all liquid is pushed out of the chamber providing the pumping. Titanium electrodes used in [33] demonstrated much better stability at high current density than Pt electrodes.

Here we describe a membrane actuator that uses as the driving process the alternating polarity electrolysis. The device is tested in different regimes.

2. Experimental

Design of the actuator and a ready-to-use device are shown in Fig. 1. The device has a working chamber with metallic electrodes

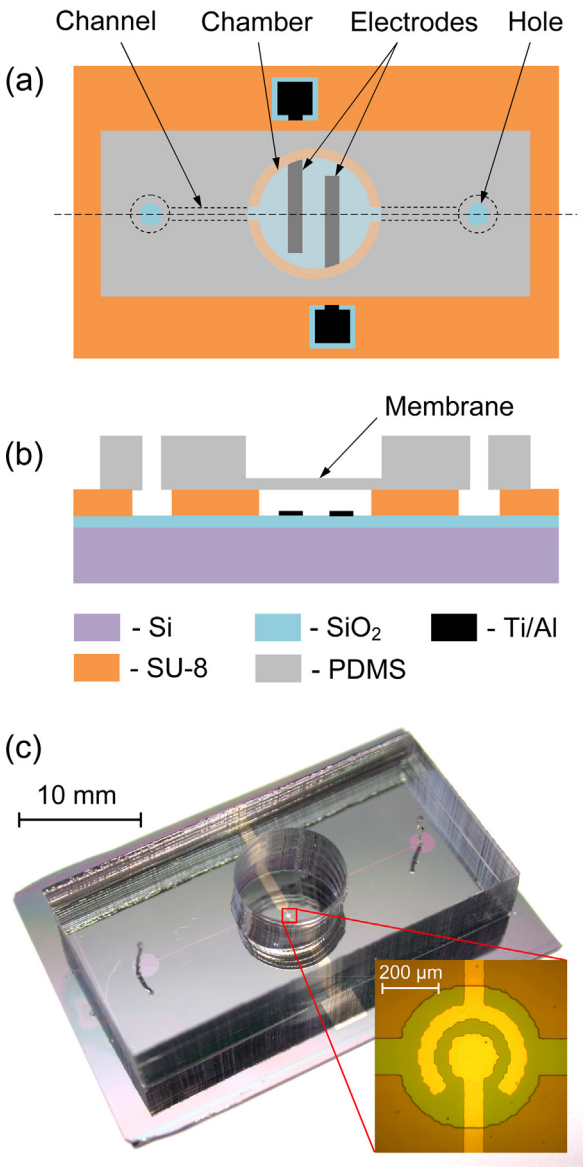

Fig. 1. Design of the actuator: (a) the top view; (b) cross section along the dashed horizontal line in (a). Ready to use actuator is presented in panel (c). The inset shows a zoomed view of the working chamber.

inside, channels to fill the system with the electrolyte, and holes for connection with microfluidic tubes. The diameter of the chamber is 500 μm and its height is 8 μm. An oxidized silicon substrate is used as the bottom wall, the side walls are made of cured SU-8 resist, and the upper wall is a flexible PDMS membrane with a thickness of 30 μm. The electrodes have a circular shape; the external electrode has a larger diameter of 380 μm and the internal one is 180 μm in diameter. The electrodes contain two metallic layers deposited by magnetron sputtering. The bottom layer is 500 nm thick Al, which is necessary to reduce the resistance of the contact lines. As the working layer we are using titanium (500 nm), which demonstrates very good stability at high current density flowing through the electrolyte.

A molar solution of sodium sulfate Na_2SO_4 in distilled water is used as the electrolyte. This solution provides high current through the electrolyte, which is necessary to produce high concentration of nanobubbles; it has neutral pH, which is preferable to exclude etching of aluminum; only hydrogen and oxygen are generated in this solution. As an alternative variant one can use ammonium sulfate