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A fast and strong microactuator powered by explosion of a hydrogen-oxygen mixture

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Abstract. An electrochemical actuator is demonstrated that uses the periodic explosions of hydrogen and oxygen gases in a microchamber with a volume of 3.1 nl. The gases are generated in the form of nanobubbles during alternating polarity electrolysis. The device operates at a frequency of up to 10 Hz. The stroke of the membrane can reach 100 μm, which is an order of magnitude larger than the deflection in the non-explosive mode. No significant wear of the device is observed after 40 000 explosions in the chamber. The output force is measured by loading the membrane with different objects. The actuator develops a force at least 0.5 N, significantly outperforming other actuators in terms of force density.

Keywords: electrochemical actuator, membrane, alternating polarity electrolysis, nanobubbles, explosion, force

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Быстрый и сильный микроактюатор на основе взрыва водород-кислородной смеси

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Аннотация. Исследованы рабочие характеристики быстрого электрохимического актюатора, использующего взрыв стехиометрической смеси водорода и кислорода в закрытой камере объемом 3.1 нл. Ход мембраны составляет около 100 мкм и на порядок превышает отклонение при работе без взрыва. Актюатор развивает силу 0.5 Н и существенно превосходит актюаторы других типов по этому параметру.

Ключевые слова: электрохимический актюатор, мембрана, электролиз переменной полярности, нанопузыри, взрыв, усилие

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Introduction

The development of microfluidic technology has opened up new possibilities in various fields, including chemical analysis, cellular research, rapid disease diagnosis, and other areas of biology and medicine. These systems can deliver drugs directly to affected organs or tissues, minimizing side effects and enhancing treatment efficacy [1]. A key component of these microfluidic devices is the drug delivery module, which consists of a micropump that dispenses fluid from an integrated reservoir to the body. The pump uses an actuator to create a back-and-forth motion of the membrane, which is essential for accurate and efficient drug delivery. The actuator must be small, generate a significant force, and can be manufactured using conventional microelectronic techniques. Electrochemical actuators are well-suited for this purpose, as they consist of a chamber containing two electrodes immersed in an electrolyte solution. During electrolysis, gas bubbles form in the chamber, pushing the membrane and causing it to move back and forth.

Conventional electrochemical actuators have a long response time due to the slow gas recombination process. Recently, a new type of actuator has been developed that can operate at much higher frequencies than conventional actuators [2]. This new actuator is capable of delivering an ultra-precise dosage of 0.14 nl/cycle, but it has a relatively low pumping rate [3]. However, by using a novel mode of operation that involves the merging of hydrogen and oxygen nanobubbles into a larger microbubble, the flow rate can be significantly increased. In this study, we investigate the performance of this actuator when it operates in this explosive mode.

Materials and Methods

The actuator is schematically illustrated in Figure 1. It is fabricated on a 460 μm thick silicon substrate coated with a 1 μm thick thermally grown SiO_2 layer. On the dielectric layer, bilayer electrodes are formed by magnetron sputtering. The lower layer is a 500 nm thick aluminum layer that reduces the resistance of the electrodes, and the top layer is 150 nm thick ruthenium layer that guaranties resistivity to mechanical action of nanobubbles. The electrodes are located inside the working chamber with a diameter of 500 μm, and the chamber walls are made of SU-8 photoresist with a thickness of 16 μm. The chamber is closed by a flexible membrane made of 30 μm thick polydimethylsiloxane.

The operation principle is the following. One electrode is grounded, and a series of voltage pulses of alternating polarity with a frequency of 500 kHz is applied to the second electrode. The amplitude of pulses is chosen so that the concentration of H_2 and O_2 nanobubbles reaches a critical value. Densely packed nanobubbles merge into a microbubble containing a stoichiometric mixture of gases and electrolyte nanodroplets. Due to these nanodroplets, a combustion reaction is spontaneously ignited, leading to an explosive expansion of the bubble and a rapid upward movement of the membrane. During the reaction, the gases rapidly turn back into water causing the membrane to return to its initial position after the explosion.

The exploding microbubble leads to a sharp decrease in the current flowing through the electrodes. This drop is detected by the special electronics built into the pulse generator. When an explosion occurs, the generator stops sending the driving signal to prevent secondary, less powerful explosions and the accumulation of gas in the chamber. The movement of the membrane stroke is monitored by a video camera attached to an optical microscope. At the exact moment of the explosion, the generator sends a triggering pulse that initiates the process of taking pictures.

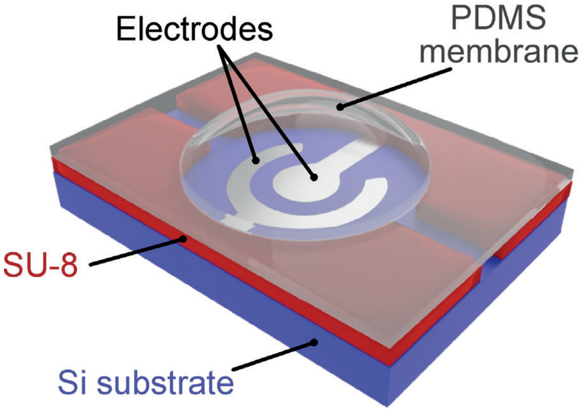

Fig. 1. Design of the actuator

To measure the output force, a metal ball with a diameter of 1.05 mm and a mass of 4.1 mg and a metal plate with a size of 3.9×2.0×0.6 mm and a mass of 35 mg are placed on the membrane. The movement of the load is recorded at a rate of 240 frames per second.

Results and Discussion

A photograph of the membrane after it has been deflected by an explosion is shown in Figure 2. Due to the rapid motion of the membrane, the image appears blurred. The average deflection of the membrane is about 100 μm, which is significantly larger than the deflection in the non-explosive regime.

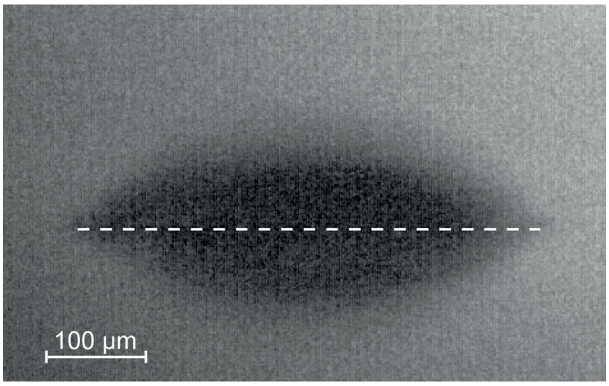

Fig. 2. A photograph of the membrane during the explosion, side view. The dotted line marks the initial position

Interrupting the series of pulses after the explosion reduces the amount of residual gas in the chamber, allowing for cyclic operation at a frequency of up to 10 Hz, which is in order of magnitude higher than the previous value [4]. The explosions may damage the sample due to cavitation. For electrodes located in unconfined space filled with the electrolyte, several thousand explosions can cause cracks and material detachment as shown in Fig. 3, *a*. However, for the actuator confined in the chamber no signs of wear even after 40 000 explosions, as shown in Fig. 3, *b*. The reason is related to the asymmetric position of the microbubble relative to the center of the chamber. Thus, the actuator is able to operate in the explosive mode for a long time.

The actuator throws the loading ball to a height h up to 29 mm and delivers the energy $E = m \cdot g \cdot h = 1.2$ μJ, where m is the ball mass. The initial velocity of the ball is $v = (2 \cdot g \cdot h)^{1/2} = 0.75$ m/s. According to the current waveform, the membrane deflects to its maximum for $t_0 \approx 10$ μs. Thus, the initial acceleration is estimated $a \approx v/t_0 \approx 7\,700$ g, and the output force is $F = m \cdot a \approx 0.31$ N. The actuator is able to move a heavy plate with a force of 0.5 N. Therefore, the micron-sized actuator under investigation is able to move macroscopic objects 11 000 times heavier than itself.

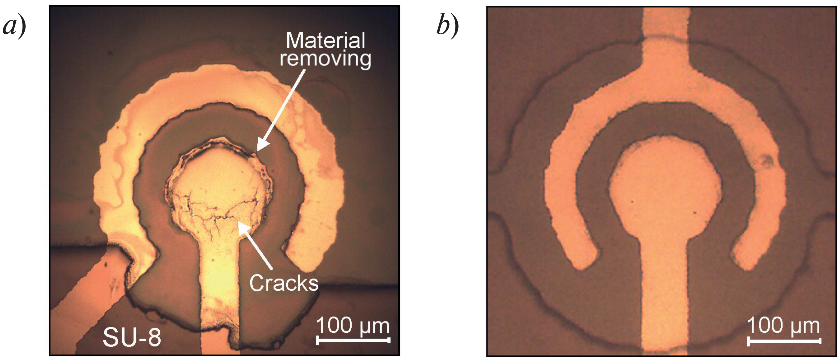

Fig. 3. Top view photographs of the electrodes: electrodes outside the chamber after 3 000 explosions (*a*); electrodes in the chamber after 40 000 explosions (*b*)

It is reasonable to compare various actuators using the force density, which is a ratio of an output force to an effective volume of the device. Electrostatic, thermal, and piezoelectric actuators are the strongest [4–6]. They can generate specific force up to several Newtons per cubic millimeter. The proposed actuator has a force density of 150 N/mm^3 that is at least one order of magnitude higher.

Conclusion

The operation of a fast electrochemical actuator in explosive mode is investigated. After the explosion, a series of pulses are interrupted, providing cyclic operation of the actuator at a frequency up to 10 Hz. The actuator can withstand more than 40,000 explosions without degradation. The membrane stroke is 100 µm, which is an order of magnitude higher than in the non-explosive mode. When a load is applied to the membrane, the actuator generates a force up to 0.5 N, which is several orders of magnitude greater than devices of comparable size can produce. The force density of the actuator is 150 N/mm^3, which is significantly higher than the most powerful devices.

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