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Fabrication of a micropump based on the fast electrochemical actuator with the PDMS membrane

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Abstract. Microfluidic systems can deliver drugs to a human body in small accurate doses. For this purpose, they have to be equipped by a compact, energy-efficient and microtechnology-compatible pump. A recently proposed micropump based on the fast electrochemical actuator meets these requirements. It contains three actuators operating in a peristaltic manner. The first version of the pump was not completely functional due to the shortcomings of the fabrication process. In this work, we proposed a modified technological route. The flexible membranes of the actuators are made of polydimethylsiloxane (PDMS) instead of SiNx, which increases the fabrication yield. The route includes the formation of the PDMS membrane on a polyester film and two steps of bonding of the membrane to a photoresist SU-8, which are the most critical operations. Details of the fabrication process are reported and optimal bonding conditions are found.

Keywords: microfluidics, micropump, electrochemical actuator, nanobubbles, bonding

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Изготовление микронасоса на основе быстрого электрохимического актюатора с ПДМС-мембраной

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Аннотация. Микрофлюидные устройства способны выполнять прецизионную доставку лекарств в тело человека. Для этой задачи они должны быть оснащены компактным и энергоэффективным микронасосом. Предложенный ранее микронасос на основе быстрого электрохимического актюатора отвечает этим требованиям. Он содержит три актюатора, работающих в перистальтическом режиме. Первая версия

насоса функционировала неудовлетворительно вследствие недостатков технологии изготовления. В этой работе предложен модифицированный технологический маршрут. В качестве материала мембраны актюатора используется полидиметилсилоксан (ПДМС), что увеличивает выход годных образцов. Технология включает нанесение ПДМС на гибкую пленку и два процесса сращивания мембраны с фоторезистом SU-8.

Ключевые слова: микрофлюидика, микронасос, электрохимический актюатор, нанопузыри, сращивание

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Introduction

Microfluidic systems are attractive for many applications. They operate with small amount of fluid and are fabricated by the means of microtechnology. A tiny microfluidic chip can do the same as bulky equipment. Labs on chip are widely used in biology and medicine for manipulation with cells [1, 2], virus and pathogen detection [3, 4], diseases diagnostics [5, 6], and other purposes. Promising microfluidic systems are small modules that deliver drugs to human body [7] or to a target organ or tissue [8]. Drug delivery modules require a compact, energy-efficient and microtechnology-compatible pump. A recently proposed micropump based on the fast electrochemical actuator satisfies these criteria [9]. The main part of the pump has a size of about of 3 mm, which is an order of magnitude smaller compared to the conventional micropumps. The pump is designed to have a flow rate of 1.5 μL/min with a dosage accuracy of 0.25 nL. The first version of the pump was not completely functional due to fabrication problems. The device has been equipped with the SiN_x membrane that was bonded to the channels made of SU-8 photoresist. The quality of bonding was sensitive to the surface imperfections, contaminants and process conditions, which led to a rather low fabrication yield. To solve this problem, we propose to make the membrane of polydimethylsiloxane (PDMS). This soft material envelopes particles and defects on the surface of SU-8, thereby preventing leakage. Here we describe a modified fabrication process of the micropump based on the fast electrochemical actuator. The most critical steps related to the formation of the PDMS membrane and its bonding to SU-8 are described in detail.

Design of the pump

The micropump contains three working chambers formed on a glass substrate in a layer of the photoresist SU-8 as shown in Fig. 1. Each chamber has a diameter of 500 μm and a height of 16 μm. The chambers are covered by a 60 μm thick PDMS membrane and filled with an electrolyte that is a molar solution of Na_2SO_4 in distilled water. Two electrodes are located inside the chamber. The electrode material is a 500 nm thick aluminium conductive layer covered by a 150 nm thick working layer of ruthenium, which ensures high durability of the electrodes. The electrodes have a circular shape that provides large deflection of the membrane compared to other designs [10]. One electrode is grounded, while a series of alternating polarity voltage pulses is applied to another electrode. Nanobubbles of hydrogen and oxygen are generated in the chamber and push the membrane up. The membrane blocks the channel with the liquid to be pumped, which is formed above the chambers. When the pulses are turned off, the nanobubbles recombine in milliseconds due to spontaneous combustion reaction [11], and the membrane returns to the initial position. Driving signals are applied in such a way that the actuators operate peristaltically and push the liquid from the inlet to the outlet [9].

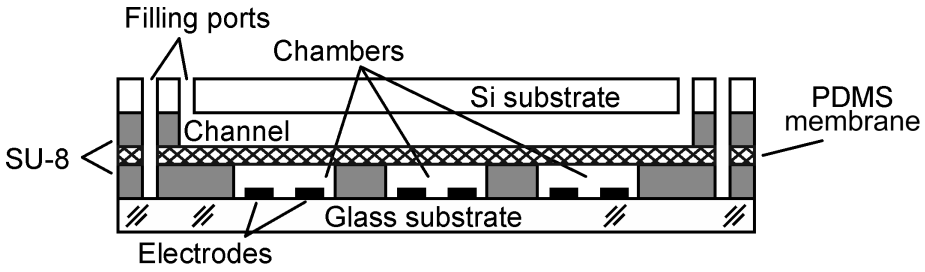

Fig. 1. A schematic cross-section of the micropump

Fabrication

A newly proposed fabrication process is shown in Fig. 2. At the first step, the electrodes are deposited on a glass substrate by magnetron sputtering. The chambers and channels for the electrolyte are formed in the SU-8 layer by spin-coating and photolithography. The soft bake and post exposure bake are carried out at 95 and 80 °C during 20 and 10 min, respectively. The hard bake is not performed in order to eliminate final cross-linking of the SU-8. Dividing trenches of 80 μm in depth are made in the substrate by a dicing saw.

Next, PDMS is spin-coated at 1000 rpm onto the polyester film (step 2). A 60 μm thick PDMS layer is obtained, which is further bonded to the SU-8 layer on the glass substrate. The adhesion between PDMS and polyester is significantly lower than that for PDMS and SU-8. The film is detached from the PDMS layer manually and openings for the channels and contact pads are punched (step 3).

Further, a silicon wafer is processed. The channels for working fluid are formed in the SU-8 layer (step 4) followed by the plasma etching of filling ports and dividing trenches from the backside (step 5). Finally, the wafer is bonded to the PDMS layer (step 6). The transparency of the glass substrate allows alignment of the substrates and observation of the meniscus during pumping. The bonded wafers are divided to separate chips by breaking along the trenches.

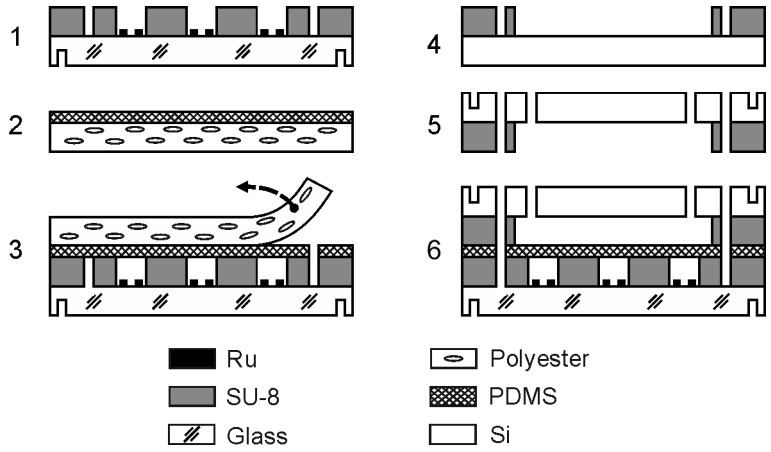

Fig. 2. Fabrication process for the micropump

The proposed route includes two steps of bonding PDMS to SU-8. The bonding is carried out by N_2 plasma treatment of the PDMS layer followed by pressing it manually to the SU-8 surface and heating the sample to initiate the N-C bond [12]. This process is the most critical part of the route. Too high pressure and too high power of the plasma produce cracks on the PDMS surface, while too low values are not enough for activation of amino groups. Both cases lead to poor adhesion and leaks of the liquids. Therefore, optimal parameters for the bonding process must be found.

The optimal parameters for the treatment have been chosen. A piece of PDMS with a size of 1×1×1 cm^3 is bonded to the SU-8 layer spin-coated on a Si substrate. Plasma treatment of PDMS is performed using the Diener Atto low-pressure plasma cleaner. Plasma power, nitrogen

pressure and treatment duration are varied for reaching the strongest adhesion between PDMS and SU-8. The power takes the value from 50 to 300 W, while the pressure is from the range of 0.1 to 0.4 mbar. The plasma exposure is performed during 120–1050 s. After the treatment the PDMS sample is put on the SU-8 layer. The stack is pressed to achieve a close contact of the surfaces. However, too high pressure may cause clogging the channels and chambers with PDMS, while too low pressure can leave air bubbles between the surfaces. The PDMS layer envelopes imperfections on the SU-8 surface and provides better adhesion than previously used SiN_x. The final step is the heating of the samples to 100 °C for 30 min in a drying chamber.

The bonding strength is estimated by manual detachment of PDMS from the substrate. The strongest adhesion is achieved at the pressure of 0.4 mbar, the power of 200 W, and the exposure time of 210 s. It was impossible to detach the samples without tearing the PDMS. Increasing of any treatment parameter leads to cracks on the PDMS surface. Reduction of the plasma power below 150 W leads a significant decrease of the adhesion.

Further, the optimal treatment is applied to a 60 μm thick PDMS layer fabricated on a polyester film. The layer is exposed to plasma and pressed to a Si wafer with the chambers formed in SU-8. In order to achieve an intimate contact of the surfaces, we use a 3D-printed roller made of thermo plastic urethane for pressing the samples. Gradual pressing from one edge of the stack to another avoids air bubbles. After the bonding the film is successfully detached from the PDMS layer, leaving the membrane above the chambers. In order to verify the adhesion strength, a piece of PDMS is bonded to the membrane layer using the well-known oxygen plasma treatment [13]. The detachment is impossible without tearing PDMS. Thus, the formation of the membrane is established, making us ready for the fabrication of the micropump.

Conclusions

The modified fabrication process of the peristaltic micropump based on the fast electrochemical actuator is described. The flexible membranes of the actuators are made of PDMS instead of SiN_x, which increases the fabrication yield. This soft material envelopes particles and defects on the surface of SU-8, thereby preventing leakage. The bonding of PDMS to SU-8 is the most critical operation of the route. It is performed by N_2 plasma treatment of PDMS, pressing it to SU-8, and heating the stack. Optimal parameters for the plasma exposure are found using the trial samples. The highest bonding strength is achieved at the nitrogen pressure of 0.4 mbar, plasma power of 200 W and treatment duration of 210 s. Using these parameters, a 60 μm thick PDMS membrane fabricated on a polyester film is successfully bonded to the wafer with chambers and channels. Thus, the formation of the membrane is established, making the fabrication of the micropump possible.

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