PHYSICAL ELECTRONICS

Conference materials
UDC 53.06
DOI: https://doi.org/10.18721/JPM.163.177

Testing the fast electrochemical micropump with PDMS membrane

P.S. Shlepakov [1]✉, I.V. Uvarov [1], A.M. Abramychev [1], V.B. Svetovoy [2]

[1] Valiev Institute of Physics and Technology RAS, Yaroslavl Branch, Yaroslavl, Russia;

[2] A.N. Frumkin Institute of Physical Chemistry and Electrochemistry RAS, Moscow, Russia

✉ p.shlepakov@bk.ru

Abstract. Microfluidic systems are widely used in various applications, including precise delivery of drugs into organs or tissues. The drug delivery system should have a compact pump with a high flow rate and precise dosage accuracy. In this work, we propose a novel micropump based on an electrochemical actuator that meets these requirements. It contains a glass substrate with three actuators, and a silicon substrate with a channel for a pumped liquid. Side walls of the actuators and channels are made of photoresist SU-8. The pumping is performed peristaltically. The working part of the pump has a size of 3 mm^3, which is an order of magnitude smaller in comparison with conventional devices. Compact size ensures ultra-precise dosage of 0.14 nl that is necessary for drug delivery systems. Design and testing procedure are described in detail, and working characteristics are provided.

Keywords: MEMS, microfluidics, micropump, alternating polarity electrolysis, electrochemical actuator

Funding: This work is supported by the Russian Science Foundation, Grant No. 18-79-10038 and the program No. FFNN-2022-0017 of the Ministry of Science and Higher Education of Russia for Valiev Institute of Physics and Technology of RAS.

Citation: Shlepakov P.S., Uvarov I.V., Abramychev A.M., Svetovoy V.B., Testing the fast electrochemical micropump with PDMS membrane, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 423–427. DOI: https://doi.org/10.18721/JPM.163.177

Материалы конференции
УДК 53.06
DOI: https://doi.org/10.18721/JPM.163.177

Тестирование быстрого электрохимического насоса с ПДМС мембраной

П.С. Шлепаков [1]✉, И.В. Уваров [1], А.М. Абрамычев [1], В.Б. Световой [2]

[1] Ярославский филиал Физико-технологического института им. К.А. Валиева РАН, г. Ярославль, Россия;

[2] Институт физической химии и электрохимии им. А.Н. Фрумкина РАН, Москва, Россия

✉ p.shlepakov@bk.ru

Аннотация. Микрофлюидные системы способны выполнять прецизионную доставку лекарств к органам человека. Для этой задачи им необходим компактный насос с высоким расходом жидкости и точной дозировкой. Предложенный в работе насос на основе быстрого электрохимического актюатора отвечает указанным требованиям. Устройство содержит три актюатора с ПДМС мембраной, изготовленные на стеклянной подложке, и канал для перекачиваемой жидкости на кремниевой подложке. Боковые стенки актюаторов и канала выполнены из фоторезиста SU-8. Перекачка жидкости осуществляется перистальтическим методом. Рабочая часть насоса имеет объем 3 мм^3, что на порядок меньше по сравнению с классическими устройствами. Компактные размеры обеспечивают сверхточную дозировку 0,14 нл. Рабочие характеристики подходят для систем доставки лекарств. В работе описана конструкция устройства и процесс тестирования.

Ключевые слова: МЭМС, микрофлюидика, микронасос, электролиз переменной полярности, электрохимический актюатор

Финансирование: Работа выполнена при финансовой поддержке РНФ, проект № 18-79-10038 и в рамках Государственного задания ФТИАН им. К.А. Валиева РАН Минобрнауки РФ по теме № FFNN-2022-0017.

Ссылка при цитировании: Шлепаков П.С., Уваров И.В., Абрамычев А.М., Световой В.Б., Тестирование быстрого электрохимического насоса с ПДМС мембраной // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 423–427. DOI: https://doi.org/10.18721/JPM.163.177

Introduction

A microfluidic system is a chip with micron-sized channels and chambers for liquid. It is used for many tasks in biology [1, 2], chemistry [3, 4], and medicine [5, 6], including delivery of drugs directly to organs and tissues. This method significantly enhances the therapy. The lack of compact and power-efficient pumps limits a widespread use of implantable drug delivery systems. As a rule, the liquid is pumped by a reciprocating membrane driven by an actuator that determines the pumping performance. Several actuation principles are known to date, but an electrochemical method is the most suitable for drug delivery systems. Electrochemical actuator is a chamber with two electrodes inside, which is filled with electrolyte and closed by a flexible membrane. DC electrolysis of water generates gas bubbles in the electrolyte, which create an extra pressure and push the membrane. The main disadvantage of this actuator is the slow dissolution of gases, which usually takes several minutes. Thus, the pump cannot operate at the required frequency. A novel electrochemical actuator was proposed recently [7]. Alternating polarity voltage pulses generate hydrogen and oxygen nanobubbles which are dissolved in several milliseconds due to spontaneous combustion reaction. The pump based on this actuator has the working part of 3 mm^3 in size, which is about ten times smaller in comparison with conventional devices. Estimated flow rate and dosage accuracy are of 0.37 μL/min and 0.25 nL, respectively. This work describes the micropump design, testing procedure and performance.

Materials and methods

A schematic cross-section of the micropump is shown in Fig. 1. The electrodes are fabricated on a glass substrate Borofloat 33 by magnetron sputtering. 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 [8]. Chambers of the actuators and channels for the electrolyte are formed in the SU-8 layer by spin-coating and photolithography. Each chamber has a diameter of 500 μm and a height of 16 μm. A polydimethylsiloxane (PDMS) membrane with the thickness of 60 μm is formed by spin-coating on a flexible polyester film and bonded to the photoresist SU-8. The bonding is performed by N_2 plasma treatment of the PDMS layer followed by pressing it to the SU-8 surface and heating the sample to initiate the N-C bond [9]. After the bonding the film is successfully detached from the PDMS layer, leaving the membrane above the chambers. Further, a silicon substrate with a 10 μm high channel for a working liquid is bonded to the PDMS membrane. The channel is also made of SU-8. Filling ports in the silicon substrate are formed by deep anisotropic plasma etching [10].

The micropump works by peristaltic deflection of actuators in a cycle of six steps, as shown in Fig. 2, *a*. At each step, the working channel is blocked by at least one membrane, which prevents the reverse liquid flow. The working cycle is provided by a driving voltage shown in Fig. 2, *b*.

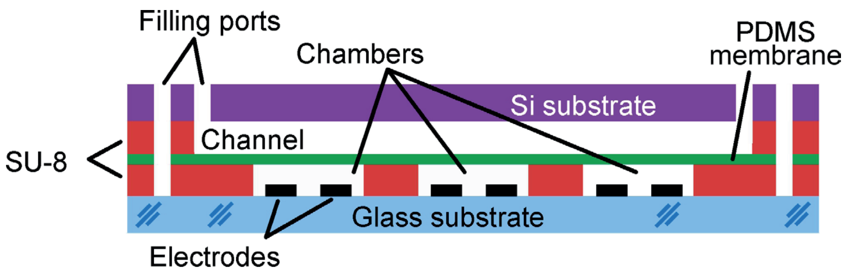

Fig. 1. A schematic cross-section of the micropump

Alternating polarity pulses with a frequency of 500 kHz and an amplitude of 5 V are formed with a homemade generator based on the STM32G474RBT3 microcontroller. The pulses are applied to each actuator during an active time t_a = 20 ms. The membrane moves upwards and pushes the liquid from the channel. During a passive time t_p = 20 ms no pulses are applied and the membrane returns to the initial position. The signal is the same for all the actuators, but for the second and third actuator it is shifted for $2t_a/3$ and $4t_a/3$. The cycle has a duration of $t_c = t_a + t_p$ = 40 ms. Thus, the working frequency is $f_c = 1/t_c$ = 25 Hz.

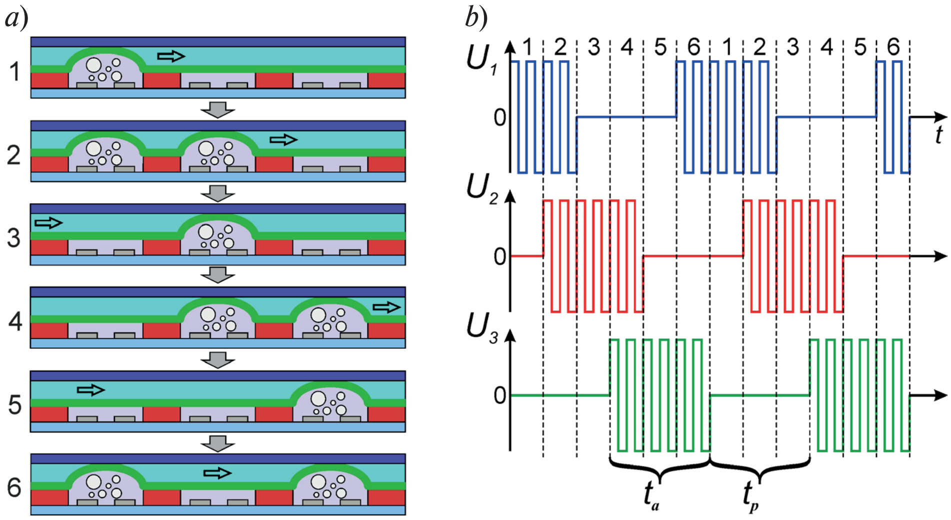

Fig. 2. Working principle of the micropump: (*a*) operation sequence of the actuators and (*b*) driving voltage applied to the actuators

The fabricated chip is shown in Fig. 3. It has a size of 20×30×1 mm with the working part of 3 mm^3. A 3D-printed sample holder is used for connecting microfluidic tubes to fill the pump with water solution of Na_2SO_4 and distilled water. Six tungsten probes are installed on the contact pads and provide driving signals to the electrodes. The meniscus of the working liquid is followed through the glass substrate using a microscope equipped by a camera Moticam 1SP.

The dosage is measured by applying one period of driving signals. The displaced volume is found by tracking the meniscus in the working channel. In order to measure the flow rate, several tens of periods are fed to the electrodes. A path of the meniscus multiplied by the height and width of the channel gives the pumped volume, which is divided by the time of pumping.

Results and discussion

The micropump provides the dosage of 0.14 nl, which is 40% lower than the estimated value. The reason is a reduced membrane deflection due to the presence of the working liquid in the channel. The expected stroke of 5 μm is reached at the pulse amplitude of 11 V and atmospheric air above the membrane. The liquid loads the membrane and reduces the stroke. The measured dosage corresponds to the deflection of 2.9 μm. Conventional devices have a dosage of tens of nanoliters [11, 12]. Thus, the proposed micropump demonstrates ultra-precise dosage.

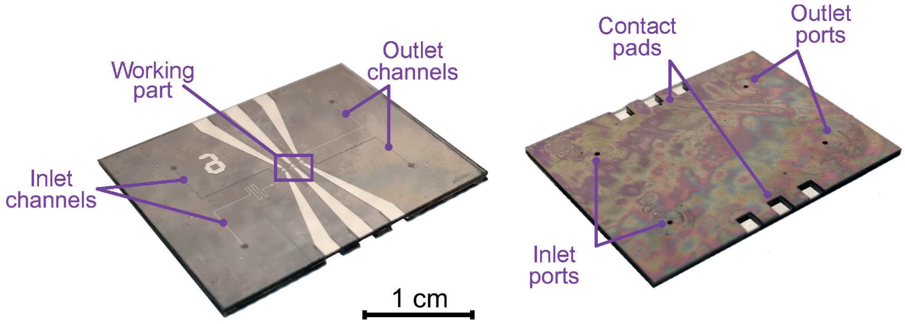

Fig. 3. Fabricated micropump: front side (*a*), back side (*b*)

At the flow rate testing, the meniscus moves for 1460 μm during 1.7 s. These values correspond to the flow rate of 0.06 μl/min, which is about 6 times lower than was predicted. Such a large discrepancy cannot be explained only by the reduced membrane deflection. Another reason is a backpressure that increases during pumping. It is reasonable to compare micropumps of various size by the normalized flow rate R/V, which is a ratio of the flow rate to the volume of the working part. The proposed pump has $R/V = 0.02$ μl/(min·mm^3). For conventional electrochemical devices this value is about 0.05 μl/(min·mm^3) [13]. At the same time, pumps of another type provide the flow rate from 1 to 1000 μl/min at the working part volume of more than 100 mm^3 [14]. Thus, R/V of these devices is below 0.02 μl/(min·mm^3). The proposed micropump has a comparable value. Adjusting the actuator stroke to the channel height will eliminate the backflow and improve the performance. It may be achieved by using the explosive regime that ensures much higher membrane deflection [7].

Conclusions

The peristaltic micropump based on the fast electrochemical actuator is presented. It contains three actuators working at the frequency of 25 Hz. The pump provides the dosage of 0.14 nl that is an ultra-precise value in comparison with another micropumps. The ratio of the flow rate to the volume of the working part is of 0.02 μl/(min·mm^3), which is comparable to other devices. Thus, the micropump meets the requirements of implantable drug delivery systems. The flow rate may be increased by using explosive mode of the fast electrochemical actuator, which will be investigated in the future.

REFERENCES

1. **Tang W., Jiang D., Li Z., Zhu L., Shi J., Yang J., Xiang N.,** Recent advances in microfluidic cell sorting techniques based on both physical and biochemical principles, Electrophoresis. 40 (6) (2019) 930–954.

2. **Xu X., Huang X., Sun J., Wang R., Yao J., Han W., Yin M.,** Recent progress of inertial microfluidic-based cell separation, Analyst. 146 (23) (2021) 7070–7086.

3. **Fujii S.I., Tokuyama T., Abo M., Okubo A.,** Fluorometric determination of sulfite and nitrite in aqueous samples using a novel detection unit of a microfluidic device, Analytical sciences. 20 (1) (2004) 209–212.

4. **Bodor R., Madajová V., Kaniansky D., Masár M., Jöhnck M., Stanislawski B.,** Isotachophoresis and isotachophoresis—zone electrophoresis separations of inorganic anions present in water samples on a planar chip with column-coupling separation channels and conductivity detection, Journal of Chromatography. 916 (1-2) (2001) 155–165.

5. **Garcia-Cordero J.L., Maerkl S.J.,** Microfluidic systems for cancer diagnostics Current opinion in biotechnology. 65 (2020) 37–44.

6. **Luan Q., Macaraniag C., Zhou J., Papautsky I.,** Microfluidic systems for hydrodynamic trapping of cells and clusters, Biomicrofluidics. 14 (3) (2020) 031502.

7. **Uvarov I.V., Lokhanin M.V., Postnikov A.V., Melenev A.E., Svetovoy V.B.,** Electrochemical membrane microactuator with a millisecond response time, Sensors and Actuators B: Chemical. 260 (2018) 12–20.

8. **Shlepakov P.S., Uvarov I.V., Svetovoy V.B.,** Ruthenium as an electrode material for the fast electrochemical actuator, St. Petersburg Polytechnic University Journal. Physics and Mathematics. 15 (3.2) (2022) 280–284.

9. **Zhang Z., Zhao P., Xiao G., Watts B. R., Xu C.,** Sealing SU-8 microfluidic channels using PDMS, Biomicrofluidics. 5(4) (2011) 046503.

10. **Morozov O.V., Amirov I.I.,** Aspect-ratio-independent anisotropic silicon etching in a plasma chemical cyclic process, Russian Microelectronics. 36 (2007) 333–341.

11. **Dumont-Fillon D., Tahriou H., Conan C., Chappel E.,** Insulin micropump with embedded pressure sensors for failure detection and delivery of accurate monitoring, Micromachines. 5 (4) (2014) 1161–1172.

12. **Spieth S., Schumacher A., Holtzman T., Rich P. D., Theobald D.E., Dalley J.W., Zengerle R.,** An intra-cerebral drug delivery system for freely moving animals, Biomedical microdevices. 14 (5) (2012) 799–809.

13. **Yi Y., Chiao M., Wang B.,** An electrochemically actuated drug delivery device with in-situ dosage sensing, Smart Materials and Structures. 30 (5) (2021) 055003.

14. **Forouzandeh F., Arevalo A., Alfadhel A. Borkholder D.A.,** A review of peristaltic micropumps, Sensors and Actuators A: Physical. 326 (2021) 112602.

THE AUTHORS

SHLEPAKOV Pavel S.
p.shlepakov@bk.ru
ORCID: 0000-0002-1255-791X

UVAROV Ilia V.
i.v.uvarov@bk.ru
ORCID: 0000-0002-6882-0625

ABRAMYCHEV Andrey M.
irumiantsieva@bk.ru
ORCID: 0000-0002-3914-4875

SVETOVOY Vitaliy B.
svetovoy@yandex.ru
ORCID: 0000-0002-9649-5663

Received 03.07.2023. Approved after reviewing 10.08.2023. Accepted 10.08.2023.