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題目(和文)	ECFマイクロポンプのMEMS製作における最適化とこのマイクロポンプのソフトロボットへの応用
Title(English)	Study on the Optimization of MEMS Fabrication for ECF (Electro-conjugate Fluid) Micropumps and Its Application to Soft Robots
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論文要約

Thesis Outline

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Mechanical Engineering

This doctoral thesis is on the subject of an ECF (electro-conjugate fluid) micropump with TPSEs (triangular prism & slit electrode pairs) as a micro hydraulic power source for the micro actuator in the following aspects: (a) its design guidance, (b) its optimization of MEMS fabrication, and (c) its application to soft robots.

(1) Chapter 1: Introduction overviews soft robot systems as background, ECF micropumps as suitable candidates of their power sources, and the purpose & outline of this thesis. In order to satisfy the requirements of high actuation force and response time in a self-contained mini soft robot system, ECF micropumps with TPSEs are paid much attention as promising hydraulic power sources, due to the appealing advantages: (a) stable pulse-free flow, (b) low noise and friction, (c) simple structures, (d) easy MEMS fabrication, and (e) high output power. However, there are mainly three challenges in ECF micropumps and their applications to soft robot systems: 1) lack of quantitative analysis concerning dominant parameters in the TPSE integration of ECF micropumps, 2) limitation of the TPSE height up to 500 μm determined by the aspect-ratio of our current MEMS fabrication, and 3) intricate fabrication and assembly of soft robot systems due to the combination of both rigid and soft parts. In order to address the abovementioned challenges, the research purpose of this doctoral work is to investigate and increase the output performance of the ECF micropumps with TPSEs and apply the ECF micropumps with high output performance to the micro soft robots.

(2) Chapter 2: Investigation of design dominant parameters for TPSEs' integration gives us the design guidance of ECF micropumps to determine how many TPSEs in series or parallel are necessary.

Firstly, the TPSE modular concept in 2D integration (in series or parallel) is proposed and five important design parameters are identified by investigating the output performance of 13 different ECF micropumps: 1) different serialized numbers of TPSEs; 2) different paralleled numbers of TPSEs; 3) different distances between paralleled TPSEs; 4) different widths of isolated walls; and 5) with and without isolated walls. All ECF micropumps are successfully fabricated with 100% yield rate by the MEMS technology mainly combining the nickel TPSEs microfabrication with a proposed UV-LIGA technique and the microfluidic channel patterning with a thick negative photoresist. The adhesive bonding process by the spin-coated SU-8 as a bonding layer is introduced to realize effective sealing without clogging the microfluidic channels. Through characteristic experiments of the output pressure and flow rate, the critical design parameters on the pumping performance are determined. The characteristic experiments and their analysis provide a useful design guidance of ECF micropumps suitable for their applications as well as the performance optimization of ECF micropumps

(3) Chapter 3: Novel fabrication technology to increase power density of ECF micropump proposes three novel fabrication methods for higher-aspect-ratio TPSEs (their height: around 1000 μm): (a) the novel self-aligned multilayer micro-molding technology by back UV exposure; (b) the UV-LIGA fabrication with various ultrathick photoresists; and (c) a novel mold-removing method combining the CO_2 laser engraving with the O_2/CF_4 plasma etching.

First, this thesis propose a novel micro-molding of back UV exposure with self-alignment by utilizing non-transparent conductive patterns as the UV shield and transparent conductive patterns as the wiring for electroplating. Instead of transparent conductive material such as ITO, the transparency-like electrode is conceived and designed by thin metal line patterns to aim at making it a conductor and forming no KMPR patterns over the thin metal line patterns by utilizing the patterning limitation of KMPR (about 10:1 in aspect ratio). The multi-layer fabrication by the back UV exposure is successfully realized without any alignment errors by using 70 and 220 μm thickness as one thin KMPR layer. These results verify that the proposed back UV exposure can induce superior geometric profiles of KMPR molds. In the case of 500 μm KMPR thickness, the concept of transparency-like electrode is partially proved. As a result, TPSEs with a height of 440 μm are successfully fabricated. However, this thesis indicates the difficulty to realize TPSEs having higher-aspect-ratio (their height: up to 1000 μm) by using two layers of 500 μm KMPR molds, since non-designed shapes are electroformed through the void space in the upper part of the first KMPR molds.

Among many commercially available thick photoresists, this thesis chooses two different kinds of ultrathick photoresists, SU-8 and SUEX due to high UV transparency to fabricate higher-aspect-ratio TPSEs. SU-8 is a liquid-based photoresist, while SUEX is a dry-film photoresist. It is proved that both SU-8 and SUEX are superior to KMPR with respect to geometric profiles as well as aspect-ratio of the mold. As a merit of SUEX against SU-8, SUEX as a dry-film photoresist is uniform in thickness and saves processing time due to no soft baking process to evaporate solvent. However, both crosslinked SU-8 and SUEX are too stable to selectively remove the mold by wet etching without the damage of TPSEs.

To overcome the abovementioned limitation of SU-8 and SUEX, this thesis also proposes a novel mold-removing method combining the CO_2 laser engraving with the O_2/CF_4 plasma to achieve the fast, non-swelling and complete removal of ultrathick micro-molds for the UV-LIGA technology. In particular, this study quantitatively analyses the SU-8 ablation thickness with respect to the power, scanning speed and pass numbers of the CO_2 laser engraving. The ECF micropumps with 10 TPSEs in series and 5 TPSEs in parallel are employed as the typical example to demonstrate the removal of crosslinked micro-molds. The CO_2 laser engraving is utilized as the main process to remove most photoresists and the O_2/CF_4 plasma is adopted as the post-treatment to remove the remaining photoresists. It is confirmed that the proposed hybrid removal technology can remove the crosslinked ultrathick SU-8 and SUEX micro-molds effectively and efficiently.

Therefore, the novel hybrid removal technique combined with the ultrathick micro-molding process can make higher-aspect-ratio TPSEs up to 1 mm in height. Approximately two times higher-aspect-ratio TPSEs are successfully fabricated by SU-8 (TPSEs height: 970 μm) or SUEX (TPSEs height: 790 μm) with even much better shape profile than previous TPSEs by KMPR. Through the characteristic comparison results, it is concluded that the ultrathick SU-8 or SUEX micro-molding with the novel hybrid removal contributes to improving the output performance of ECF micropumps with TPSEs. Higher-aspect-ratio TPSEs are beneficial especially for the higher flow rate of ECF micropumps.

(4) Chapter 4: Robotic fingers embedding ECF micropumps introduces the hybrid 3D-printed mini finger embedding ECF micropumps on the rigid glass substrate and the total-soft micro finger embedding the novel flexible ECF micropump on the polyimide substrate as the potential applications of the ECF micropumps with high output performance.

First, a miniaturized 3D-printed hybrid finger system with built-in fluidic channels is proposed from the inspiration of the spider leg, in which two integrated ECF micropumps control two bellow-like joints respectively to realize the compliant motion. As a better substitute for conventional manufacture method, the hybrid 3D printing technology is utilized to fabricate the monolithic parts (one monolithic body with the combination of the finger body base covered with rubber sheets and two bellow-like joints, three finger body covers combined with rubber sheets) to solve the annoying problems involving complicated structures and difficult assembly for the combination of soft material and hard material. The ECF micropumps with 35 TPSEs in series only (TPSEs height: 430 μm) used to be embedded into the large finger model are successfully fabricated by MEMS process. The characteristic results show that the maximum output pressure and flow rate obtained are 127.3 kPa and 42.8 mm^3/s respectively under an applied voltage of 3.5 kV. After assembling, the driving experiments by integrated ECF micropumps under applied DC voltage are conducted and successfully validate the feasibility of the finger concept. The maximum displacements obtained in the x-direction and the y-direction are 11.4 mm and 5.2 mm respectively (finger size: $17 \times 105 \times 8$ mm^3), when the voltage of 0.9 kV is applied to both ECF micropump 1 and ECF micropump 2. However, as the disadvantage of the large finger prototype, the dynamic response is slow, about 2.2 s.

In order to overcome the slow dynamic characteristics of the large finger prototype, the optimized hybrid mini finger embedding ECF micropumps is developed. Compared with the previous large one, it possesses the smaller finger size (39% smaller than that of the previous large one) and the smaller chamber of bellow-like joints (19% smaller than that of the previous large one). The ECF micropump with 18 TPSEs in series and 2 TPSE in parallel (TPSEs height: 450 μm) is designed and successfully fabricated by the same MEMS process. The parallelized numbers of TPSEs are increased to two so as to improve the output flow rate. The characteristic results release that under an applied voltage of 3.5 kV, the output flow rate of the optimized pump is 70.3 mm^3/s, about 1.6 times of the previous one (42.8 mm^3/s). The driving experiments demonstrate that the step response is quicker (within 1s) due to the parallelized TPSEs and smaller bellows chamber, which is enough for the practical manipulation.

Second, a flexible ECF micropump is proposed and developed by fabricating TPSEs on a polyimide (PI) substrate to exhibit both outstanding flexibility and output performance even in the bending state. The commercially available PI flexible PCB (printed circuit board), which consists of five layers: 1) reinforcing plate (thickness: 1 mm), 2) adhesive layer (thickness: 20 μm), 3) polyimide layer (thickness: 50 μm), 4) copper layer (thickness: 35 μm), and 5) positive photoresist layer (thickness: a few μm), is selected as the great potential for low-cost mass-fabrication of flexible ECF micropumps with TPSEs. The UV-LIGA process with KMPR micro-molding on the PI PCB is developed to successfully fabricate the TPSEs having different height of 380 μm and 880 μm and having no damage to the PI substrate as well. In addition, the flexibility of the PI substrate having TPSEs is validated through bending by external force. The flexible bonding methods of PDMS case coated with elastic adhesive is proposed and validated to attain compact, effective and flexible sealing. Characteristic experiments of the sealed flexible ECF micropumps with TPSEs of 380 μm in height are conducted in both straight state and bending state. The characteristic results demonstrate that the proposed flexible ECF micropumps with TPSEs maintain nearly the same output performance both in the straight state and in the large bending state. Under applied voltage of 3 kV, the maximum output pressure and flow rate are about 37 kPa and 465 mm^3/s respectively.

At last, as the final research target, the total-soft micro finger (finger size: 8.3 × 27.9 × 4 mm^3) embedding the proposed flexible ECF micropump is proposed, fabricated, assembled and experimentally tested. The proposed micro finger structure is very simple and has only two parts: the sealed flexible ECF micropump at the bottom and the PDMS bellows actuator. The simple structure and decreased numbers of components simplify the assembling process. Due to excellent flexibility, the flexible ECF micropump can be directly attached to the bottom of the PDMS bellows actuator, which dramatically minimizes the volume of the whole finger system. The flexible ECF micropump chip with high output performance control the micro PDMS bellows actuator to accomplish the compliant motion. Apart from the function of the micro flexible power source, the flexible ECF micropump works as the displacement constraint element to prevent the micro finger's axial expansion and promote its bending.

(5) Chapter 5: Conclusions and future work mentions the summarized conclusions of the research work presented in the thesis. In addition, current limitations and future work are also discussed.