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SU-8 Buckled-type Microvalves Switched by Surface Tension Forces

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***Abstract*- This paper presents the design, the fabrication, and the measurement result of a novel buckled-type microvalve. This device comprises of a parylene microtube for liquid transportation and a peacock-like SU-8 capillary microstructure for switching the microvalve without external power source. The maximal spreading angles of the peacock-like structures actuated by water surface tension are experimentally tested as 204° and 15° for the cases of not integrating and integrating a parylene microtube, respectively.**

I. INTRODUCTION

It's well known that many micro-valves have no characteristic of zero dead volume [1]. In other words, micro valves don't close or open until certain volumetric amount (the dead volume) of working fluid has been pumped into or out of the controlled actuators. This deficiency almost intrinsically limits the performance of microfluidic pumps.

A buckled-type microvalve, based on parylene technology of good coating characteristics all over 3D geometries, was presented in Transducers'05 [2]. After conformally depositing parylene film around a sacrificial glass capillary, the authors removed the glass capillary by HF to obtain a parylene microtube. A certain portion of the parylene microtube can be assigned as the buckled region to stop a liquid flow, and there is no need of adding sealing parts into the buckled-type valve with almost zero dead volume. SU-8 technology has been integrated into the parylene microtube to fabricate a testing module for studying the feasibility of the device, and the turn-on angle of the buckling tube for switching liquid flow was verified as 120°. However, there is no actuator proposed for providing sufficient buckling force and controlling the buckled angle of the parylene microvalve then.

In Transducers'05, a bio-mimicking actuator made of silicone rubber was reported with a large rotating stroke using surface tension (Young-Laplace) force, which is much more dominant than other body-force effects in the micrometer scale [3].

II. DESIGN OF THE NEW ACTUATOR DEVICE

The author herein combined the bio-mimicking peacock-like microstructure shown in Fig. 1 with the previously developed parylene (buckled-type) microtube as a complete valve device. Figure 2 demonstrates this device and its functionality of switching on and off for the pipe flow will be depicted in this paper.

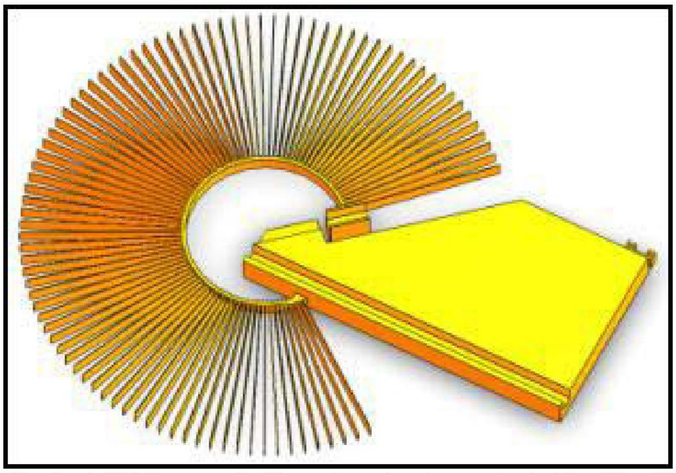

Fig. 1. A SU-8 peacock-like microstructure actuated by (liquid) surface tension force. Working liquid will be filled into the gaps of the peacock-like microstructure. The lower end of the structure is fixed on the base plate; the upper end is freely levitated.

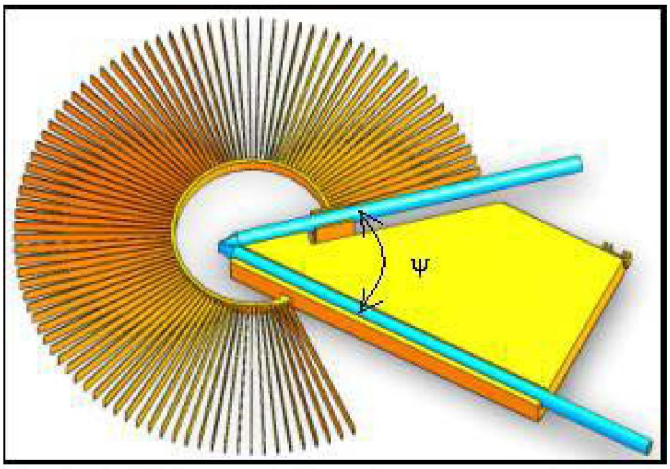

Fig. 2. A SU-8 peacock-like microstructure switching the parylene buckled tube. The spreading angle change is denoted by ψ.

The detailed operation of the device shown in Fig. 2 is conceptually described in the following. Zero position of the actuation angle ψ is assigned as 45° in this work. The pipe

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flow connecting the parylene valve tube gets closed if the angle ψ is smaller than 60°. (This fact has been verified in [2].) That is to say, the actuation angle change subject to the capillary actuation of the filled liquid among the peacock-like microstructure should be greater than 15° to ensure the opening of the pipe flow connecting the parylene valve tube. Therefore, a proper geometry design of the peacock-like capillary microstructure as a new actuator should be accomplished before the device fabrication.

Figure 3 shows a single pair of beam structures of the new actuator of Figs. 1 or 2. The liquid filled inside the gap between two capillary beam structures deduces a huge attraction force (the "negative" Laplace pressure) to pull the beams close to each other. If the capillary structures are not really collapsing or not stuck together due to the hydrophobic characteristic of the structure surfaces (e.g., SU-8 surfaces in this work), the peacock-like beam structure will restores to its original shape after the working liquid dries out exactly.

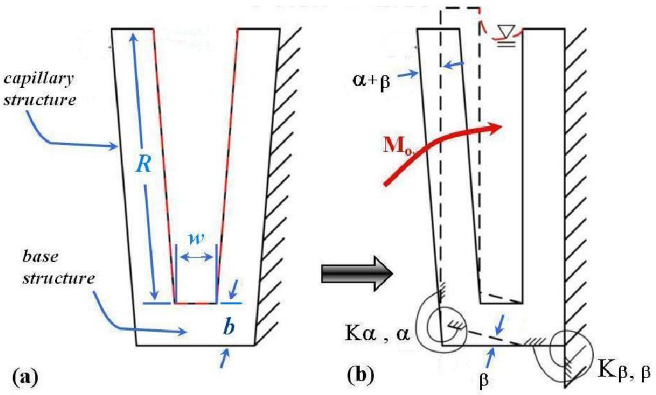

Fig. 3. A single pair of beam structures of the new actuator driven by surface tension force. The base structure is with the dimension of w in length, b in width, and H in thickness. The capillary structure is with the length of R.

Before the device fabrication, the proper geometry design of the capillary beam structure is necessary to make sure the sufficient attraction force actually existing in the actuation device. In this work, we access the energy approach to derive the surface tension force in the actuator device and estimate the actuation angle change afterward. The surface energy of the liquid column in Fig. 3, denoted by E_s, is formulated as Eq. (1).

$$E_s = \gamma_{la}\{[2w+R(\alpha+\beta)]R+[w+R(\alpha+\beta)]H\}+\gamma_{sl}H(2R+w) \tag{1}$$

where γ_{la} *and* γ_{sl} denote the surface tensions of liquid-air and solid-liquid interfaces, respectively. With the anchored assumption on the right hand side of the beam in Fig. 3, the L-shaped beam hanging on the left hand side can be regarded as two torsion springs in series. The deformed angle of the base structure (w in length, b in width, H in thickness) with a spring constant of K_β is denoted by β; whereas the actuation angle of the longer capillary structure with a spring constant of K_α is denoted by α. The strain energy stored in the deformed structure subject to the actuation of liquid surface tension force is shown in Eq. (2).

$$E_{strain} = \frac{K_\alpha}{2}\alpha^2 + \frac{K_\beta}{2}\beta^2 \tag{2}$$

By the principle of least value of the total energy for the equilibrium system depicted in Fig. 3, the derivative of the total energy (sum of surface energy and strain energy herein) with respect to the actuation angle β should be vanished.

$$K_\beta \beta = \frac{\partial E_{strain}}{\partial \beta} = -\frac{\partial E_s}{\partial \beta} = -\gamma_{la}R(R+H) = M_0 \tag{3}$$

M_o is the bending moment induced by the surface tension between two beam structures. The actuation angle β for one pair of the peacock-like microstructure is expressed as follows.

$$\beta = -\frac{\gamma_{la}R(R+H)}{K_\beta} \tag{4}$$

where $$K_\beta = \frac{EI_\beta}{w}; I_\beta = \frac{Hb^3}{12} \tag{5}$$

and the spreading angle change ψ for the N-pair of the peacock-like structures before collapsing is defined as

$$\psi = 45^\circ - N\beta = 45^\circ + \frac{12\gamma_{la}NR(R+H)w}{EHb^3} \tag{6}$$

From the qualitative aspect of the actuator design, the working liquid with larger surface tension (larger γ_{la}) or the longer capillary structure (larger R) or the finer gap (larger N and smaller w) of capillary structures are beneficial to the prominent rotating actuation of the SU-8 device. Therefore, we chose R as 2700 μm and 3400 μm, N as 210 and 175, respectively. The calculated value of the actuation angle is large enough to get the two neighboring beams close firmly.

Another interesting qualitative aspect for the surface tension-driven device is that the actuation angle change ψ is no matter with the wetting behavior (contact angle) of the capillary structure. That is, even using the hydrophobic SU-8 resist as the capillary structure (the contact angle of water on SU-8 surface is larger than 90°) in this work still doesn't deteriorate the performance of the new actuator device. There is actually no problem for us in practice to fill liquid into the gaps of the peacock-like structure made of hydrophobic SU-8.

III. FABRICATION OF THE NEW ACTUATOR DEVICE

Besides the excuses of anti-stiction during the liquid drying and not deteriorating the capability of absorbing working liquid during operation, using SU-8 as the material for the peacock-like structures in Figs. 1 and 2 has another advantage additionally. With Young's modulus of 4.4 GPa, much larger than silicone rubber in the prior art [3], SU-8 resist is good for providing enough actuation force in this work. Convenient photo-patterning of SU-8 resist with high aspect ratio and high spatial resolution is still more advantageous over other materials for us to access. The simplified fabrication process of the valve device is shown in Fig. 4.

With alignment marks defined on the substrate in advance, the multi-layer SU-8 technology [4] is used to make the peacock-like structure (the 1st layer) as well as the holding grooves (the 2nd layer) for the parylene microtube. After proper control of UV exposure and post-exposure-baking on the two SU-8 layers (steps (a) and (b) of Fig. 4), this semi-3D HARMS (high-aspect-ratio microstructure) of Fig. 1 can be achieved by only one developing process. We additionally mounted the parylene microtube on the SU-8 HARMS by adhesive in step (c), and finally release the complete valve device from silicon substrate in step (d).

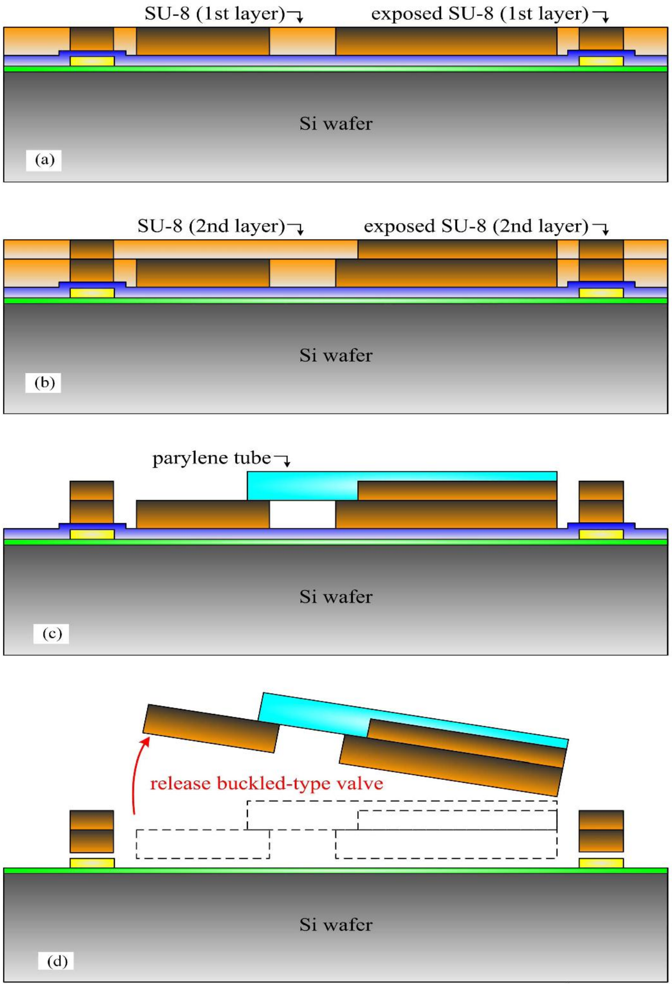

Fig. 4. Fabrication process: (a)UV exposure to the 1st SU-8; (b) UV exposure to the 2nd SU-8; (c)SU-8 developing and parylene-tube mounting; (d)device release from the substrate.

IV. ACTUATION TEST

Herein we used a very simple testing setup shown in Fig. 5 to observe the actuation angle cased by the liquid surface tension. A tweezers (the type of normally clamped) mounted in a housing with black background is used to grasp the actuator device, and such a setup is proper for taking pictures or video during the device operation by an ordinary camera.

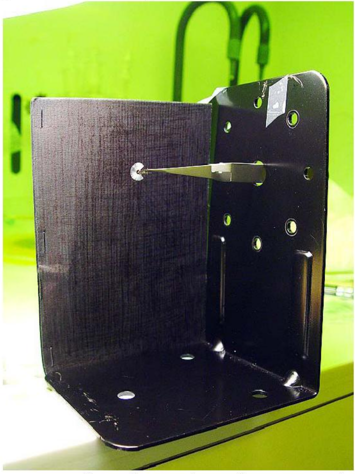

Fig. 5. Testing setup for observing the actuation angle of the new SU-8 device.

Two kinds of liquid, water and IPA, are used to activate the new device. Figure 6 shows the dramatic spreading phenomena of the fabricated SU-8 peacock-like structure of Fig. 1. No more than 5 gaps of the structure with the total gaps of 175 and 210 were observed not collapsing together. The maximal angle subject to water driving is 204°. All the testing data were plotted on Fig. 7. This wonderful performance of surface tension driving for the peacock-like microstructure encourages us to apply to activate the buckling deformation of the parylene microtube in the next step.

Figure 8 shows the angle changes of the SU-8 peacock structures integrated with parylene microtubes subject to water driving. Even the mechanical resistance of the parylene microtube against liquid surface tension makes the angle change more confined, however, the maximal angle change subject to water driving is 15° herein, just meets the minimum actuation requirement of a buckled microtube if the initial angle is less than 135° (zero position of the actuation angle ψ is assigned as 45° in Fig. 1.) In other words, if we regard the design of Fig. 2 as a valve device of enhancement-mode (normally stops flow, as shown in Fig. 8(a)), the surface tension force will pull back the buckled angle smaller than 120° (switching on and let flow go, as shown in Fig. 8(b)). Other testing data were plotted on Fig. 9.

V. DISCUSSION

- **Surface tension effect of different working fluids**

In this work, two working fluids were used. The surface tensions of DI water and IPA are 0.073 and 0.020 N/m, respectively. As the linear relation to surface tension γ_{la} shown in Eq. (6), the actuation angle ($N\beta$) activated by IPA should be only 27% of the case of DI water. However, the experimental data of IPA in Fig. 7 expand to 62~74% of DI water! It might be explained by the fact that the capillary beam structures collapsing together to deactivate the effective pulling force for the case of DI water driving.

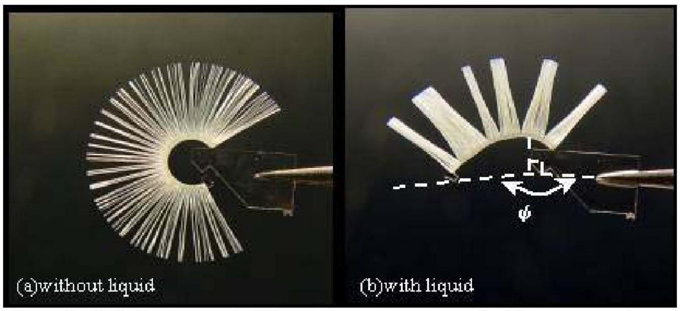

Fig. 6. SU-8 peacock-like microstructure (without parylene tube) actuated by working liquid (water.)

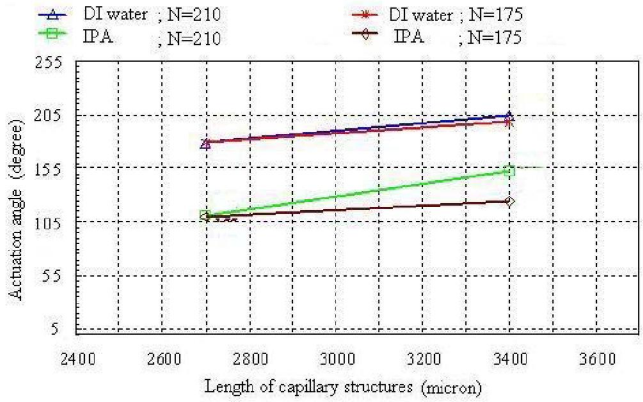

Fig. 7. Actuation angles of different peacock-like microvalves (without parylene tube) subject to different working liquids.

- **The influence of number N and gap w of capillary beams**

We can hardly find the apparent performance difference between two device designs of N=175 and 210 in Fig. 7. This observation results from the fact that the multiplying product of N and w in Eq. (6) is the total arc length of the capillary base structure. Such an invariant quantity of arc length clarifies the blurred change of the actuation angle for devices with different gaps in principle.

- **The influence of the length R of capillary beams**

According to Eq. (6), the actuation angle should be proportional to the square of the capillary beam length R. Again, the collapsing of the capillary beam structures limits the effective angular deformation of the device. In other words, a more appropriate theoretical formulation considering the collapsing phenomena of the Fig. 6 needs to be done to predict the experimental data accordantly.

Due to the much stronger stiffness of the device in Fig. 8 than Fig. 6, the collapsing of the actuator with parylene microtubes is less serious. Therefore, the actuation angles of IPA driving is about 20~33% of the case of water driving, just around the theoretical value (27%) predicted by Eq. (6). We hope to collect more experimental data of Fig. 9, and to develop its corresponding physical model to justify the optimum design in the future.

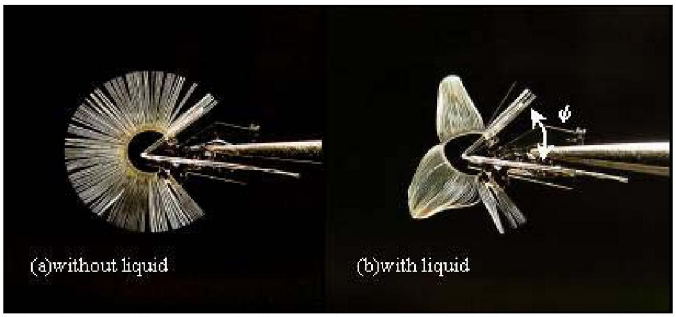

Fig. 8. SU-8 peacock-like microvalve (with parylene-tube) actuated by working liquid (water.)

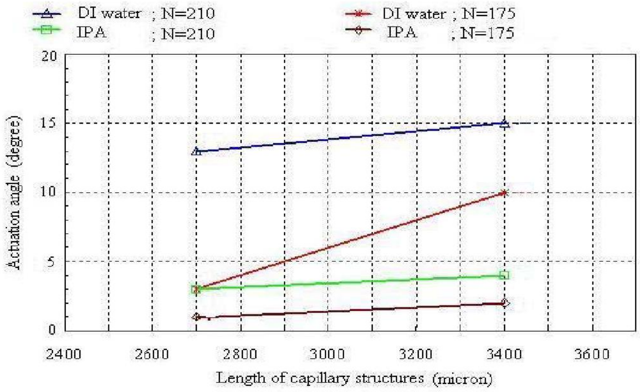

Fig. 9. Actuation angles of different peacock-like structures (with parylene tube) subject to different working liquids.

VI. CONCLUSION

A new surface tension-driven device made of parylene and SU-8 is demonstrated. The successful test of large actuation angle of the device for switching buckled-valves shows its potential in microfluidics and micro actuators with less electrical power supply.

Acknowledgement

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