Surface Tension-Driven Microvalves with Large Rotating Stroke

Lung-Jieh Yang* and Kuan-Chun Liu

Department of Mechanical and Electro-mechanical Engineering, Tamkang University, Tamsui, Taiwan 251, R.O.C.

Abstract

The design, the fabrication, and the testing result of a novel microvalve actuated by surface tension force were described in this work. This device comprises of a parylene microtube for liquid transportation and a peacock-like SU-8 capillary microstructure for switching the microvalve in a buckling deformation way without feeding external electrical power. 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.

***Key Words*: ** Surface Tension, SU-8, Parylene, Actuator, Buckling

1. 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 depositing parylene film conformally around a sacrificial glass capillary, the authors removed the glass capillary by hydrofluoric (HF) acid to obtain a parylene microtube. A certain portion of the parylene microtube can be assigned as the buckled region to stop the liquid flow inside the microtube itself, and there is no need of adding sealing parts into the buckled-type valve with the characteristic of 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 integrated no microactuator in the device then. And no proper mechanism was proposed for providing sufficient buckling force and for controlling the buckled angle of the parylene microvalve, either.

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]. The author herein would like to substitute the material of silicone rubber with the photo-patternable, high aspect-ratio SU-8 (negative-toned) resist. In other words, we combined the concept of the biomimic peacock-like microstructure shown in Figure 1 with SU-8 technology and with the previously developed parylene (buckled-type) microtube to develop a complete novel microvalve, shown as Figure 2, to have the function of switching on and off for the microfluidic transportation. Figure 2 demonstrates this device and its functionality of switching flow in the pipe will be depicted in the following.

2. Design of the New Actuator Device

The device of Figure 2 shows that the zero position

*Corresponding author. E-mail: Ljyang@mail.tku.edu.tw

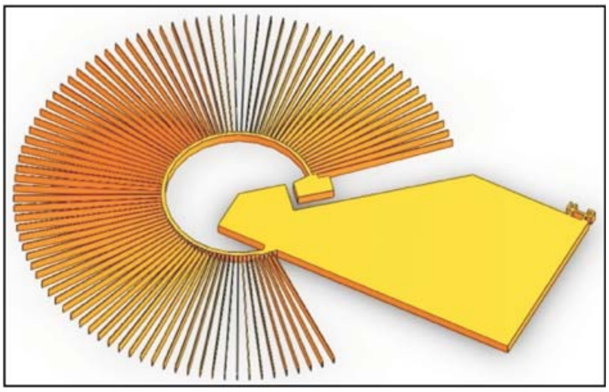

Figure 1. A SU-8 peacock-like microstructure actuated by (liquid) surface tension. Working liquid will be filled into the gaps of the peacock-like microstructure. The lower end of the structure is fixed on the base; the upper end is freely levitated.

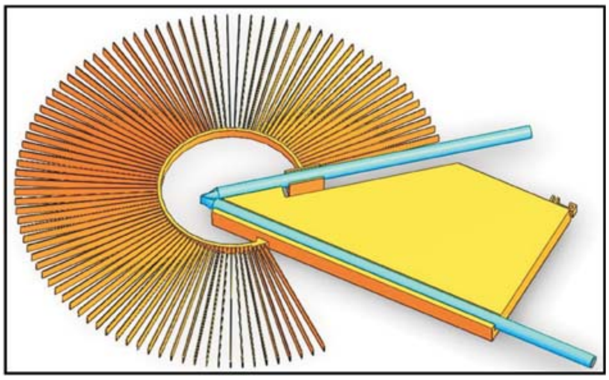

Figure 2. A SU-8 peacock-like microstructure switching the parylene buckled tube. The spreading angle change is denoted by ψ.

of the actuation angle ψ is assigned as 45° in this work. The pipe 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 Figures 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 neighboring beams close to each other. Sub-

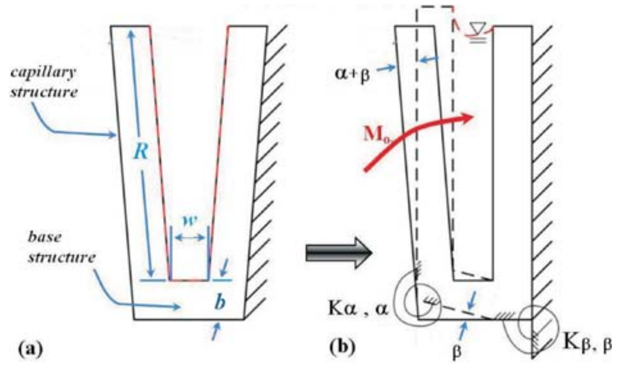

Figure 3. A single pair of beam structures of the new actuator driven by surface tension force. The base structure is with the dimension of w in length, b in width, and H in thickness. The capillary structure is with the length of R.

ject to the hydrophilic case of all microstructure surfaces, the capillary collapsing of the beam structures would not separate again forever, and it causes the catastrophic surface sticking issue in the micromachinings. However, if the capillary structures are not really collapsing or not stuck together due to the hydrophobic characteristic of the structure surfaces (for example the SU-8 surfaces in this work), the peacock-like beam structure will restores to its original shape after the working liquid dries out exactly.

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 equation in the actuator device and estimate the actuation angle change by the surface tension equation afterward. The surface energy of the liquid column in Figure 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 Figure 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 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 action (minimum value) of the total energy for the equilibrium system depicted in Figure 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, i.e.,

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

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.

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

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

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, we still found that water stays among the gaps of the peacock-like structures and don't deteriorate the actuating performance of the new device anymore. There is actually no problem for us in practical experiment to fill liquid into the gaps of the peacock-like structure made of hydrophobic SU-8.

3. Fabrication of the New Actuator Device

Besides the excuses of anti-sticking during the liquid drying and not deteriorating the capability of absorbing working liquid during operation, the using of SU-8 resist as the material for the peacock-like structures in Figures 1 and 2 has several advantages additionally. With Young's modulus of 4.4 GPa, much larger than silicone rubber in the prior art [3], SU-8 resist as the mechanical material here is good for sustaining enough strength for transferring the actuation force from the surface tension effect in this work. Even we take the risk of the intrinsic fragile property SU-8, there still exists a success window for us to access if the maximum stress in the SU-8 not exceeding its fracture limit.

Moreover, the convenient photo-patterning of SU-8 resist with high aspect-ratio and high spatial resolution convinces us of choosing it as the more advantageous candidate over other materials. The simplified fabrication process of the valve device is demonstrated in Figure 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 Figure 4), this semi-3D HARMS (high-aspect-ratio microstructure) of Figure 1 can be achieved by only one developing process concisely. We additionally mounted the parylene microtube on the SU-8 HARMS by adhesive in step (c), and finally release the complete valve device from the silicon substrate in step (d). The device size is about 8 mm.

4. Actuation Test

Herein we used a very simple testing setup shown in

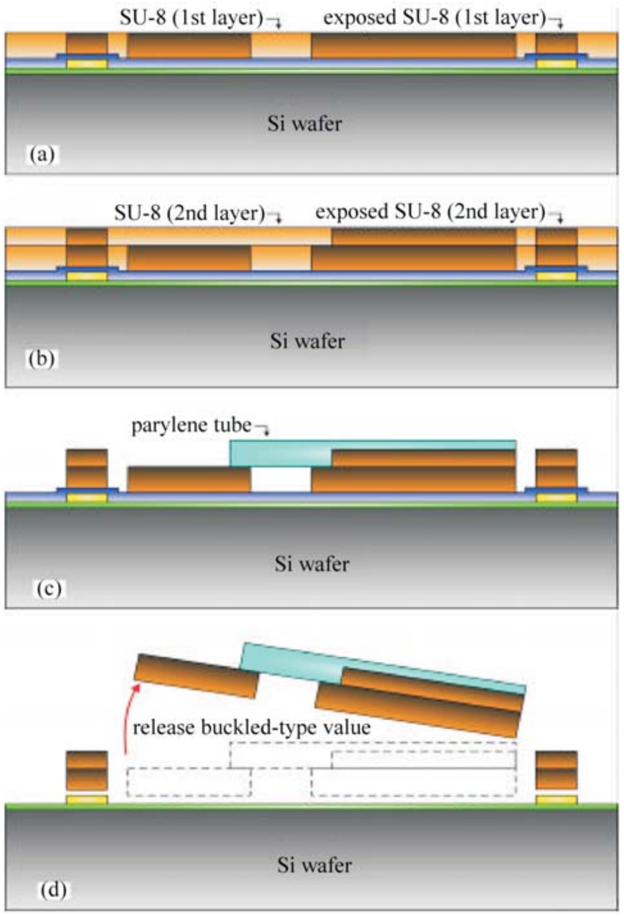

Figure 4. Fabrication process: (a)UV exposure on the 1st SU-8 layer (peacock-like structure); (b) UV exposure on the 2nd SU-8 layer (holding grooves); (c)SU-8 developing and parylene-tube mounting; (d)device releasing from the substrate.

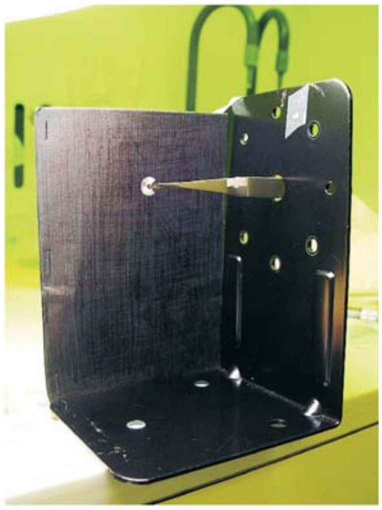

Figure 5. Testing setup for observing the actuation angle of the new SU-8 device. The picture of the actuation movement of the SU-8 device is taken by an ordinary camera.

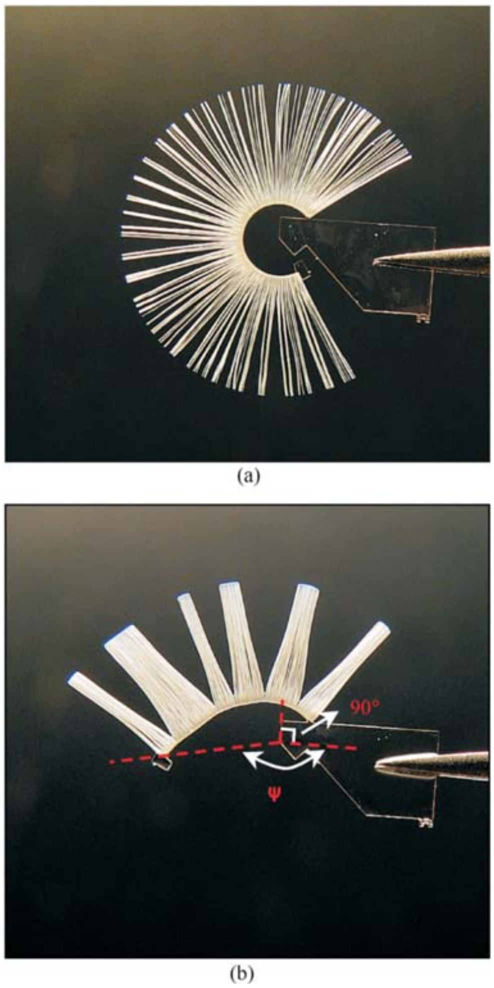

Figure 6. SU-8 peacock-like microstructure (a)without parylene tube; (b) actuated by working liquid (water.)

Figure 5 to observe the actuation angle cased by the liquid surface tension. A tweezers (the type of normally clamped or with closing beaks, instead of the opening type) mounted in a steel housing with black back-plate is used to grasp the SU-8 actuator device in the air firmly. The black back-plate provides nothing but a good contrast to the white color of SU-8 microstructures subject to good illumination aside. Such an experimental setup is proper enough for us to take pictures or video recording easily during the device operation by an ordinary camera or a video-cam.

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 Figure 1. No more than 5 gaps of the structure with the total gap number 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 Figure 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-like 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 Figure 1.) In other words, if we regard the design of Figure 2 as a valve device of enhancement-mode (normally stops flow, as shown in Figure 8(a)), the surface tension force will pull back the buckled angle smaller than 120° (switch on the valve and let flow go, as shown in Figure 8(b)). Other testing data were plotted on Figure 9.

5. Discussion

After the working feasibility of the buckled valve was approved in the previous section, the qualitative comparison between the experiment results and theoretic prediction will be issued and discussed preliminarily as below.

● **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 ten-

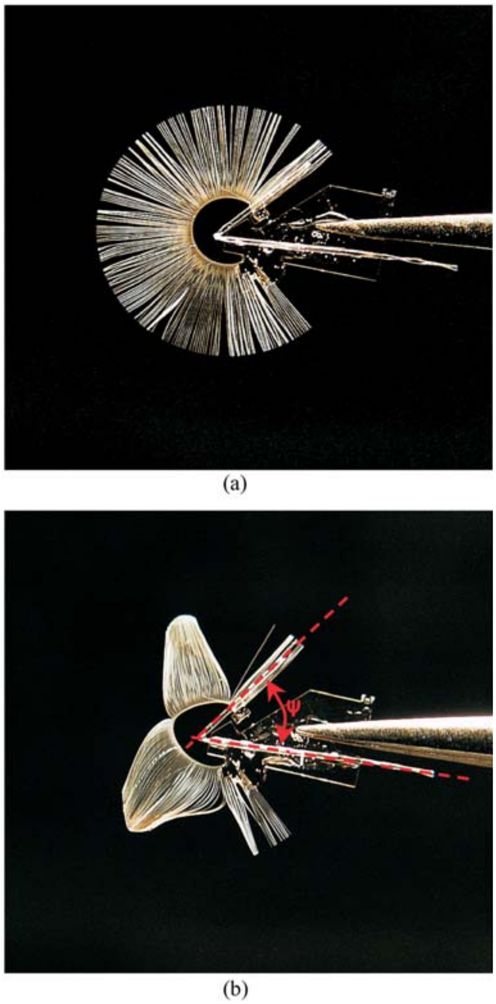

Figure 8. SU-8 peacock-like microvalve (a)with parylene-tube; (b)actuated by working liquid (water.)

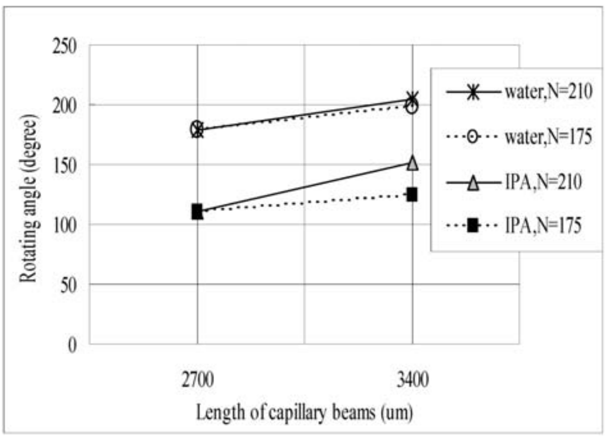

Figure 7. Actuation angles of different peacock-like microvalves (without parylene tube) subject to different working liquids.

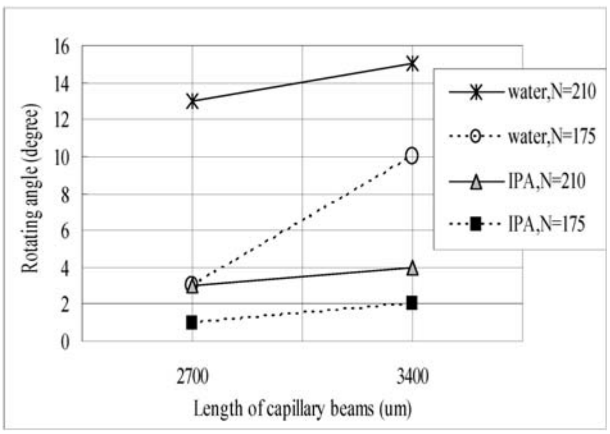

Figure 9. Actuation angles of different peacock-like structures (with parylene tube) subject to different working liquids.

sion 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 Figure 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.

● **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 Figure 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 Figure 6 needs to be done to predict the experimental data accordantly.

Due to the much stronger stiffness of the device in Figure 8 than Figure 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 Figure 9, and to develop its corresponding physical model to justify the optimum design in the future.

6. Conclusion

A new surface tension-driven device made of parylene and SU-8 in a hybrid way 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.

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Manuscript Received: Mar. 14, 2007
Accepted: Apr. 11, 2007