

Analysis and Evaluation of Capillary Passive Valves in Microfluidic Systems Using a Centrifugal Force

Han-Sang Cho*, Ho-Young Kim***, Ji-Yoon Kang*, Seung-Min Kwak* and Tae-Song Kim**

Abstract - This work reports the theoretical and experimental investigations of capillary burst valves to regulate liquid flow in microchannels. The theoretical analysis uses the Young-Laplace equation and geometrical considerations to predict the pressure at the edge of the valve opening. Numerical simulations are employed to calculate the meniscus shape evolution while the interface is pinned at the valve edge. Microchannels and valves are fabricated using soft lithography. A wafer-rotating system, which can adjust the driving pressure by rotational speed, induces a liquid flow. Experimentally measured valve-bursting pressure agrees with theoretical predictions.

Keywords: capillary burst valve, centrifugal force, microfluidics, modeling, soft lithography

1. Introduction

In microfluidic systems, valves are essential components to control the sequence of bio/chemical analyses. Among various valve schemes proposed to date [1, 2], the capillary passive valve is especially advantageous because it is insensitive to physicochemical properties of the liquid and easy to fabricate by rapid prototyping [2, 3]. Although its basic concepts have been previously empirically verified [2], an understanding of its physical properties is still far from complete. Recently, delicate body forces generated in rotational motion have been studied with the purpose of driving microfluid [1, 2, 4]. This work rigorously analyzes the hydrodynamics of the capillary passive valve for the first time. Numerical simulations are conducted to predict meniscus shape evolution while the interface is pinned. Furthermore, the microfluidic valve and rotational wafer system is fabricated and driven by centrifugal force and its operation is visualized by a triggered video system.

2. Theoretical Analysis

2.1 Pressure Difference in a Rotating System

In this work, we employ a rotating system to drive liquid flow. The driving pressure by a centrifugal force exerted on the liquid in a channel is written as

$$\Delta P_c = \frac{1}{2} \rho \omega^2 (r_2^2 - r_1^2) \quad (5)$$

where ρ is the liquid density, ω is the constant angular velocity, and r_1 and r_2 are the radii as indicated in Fig. 1 (a).

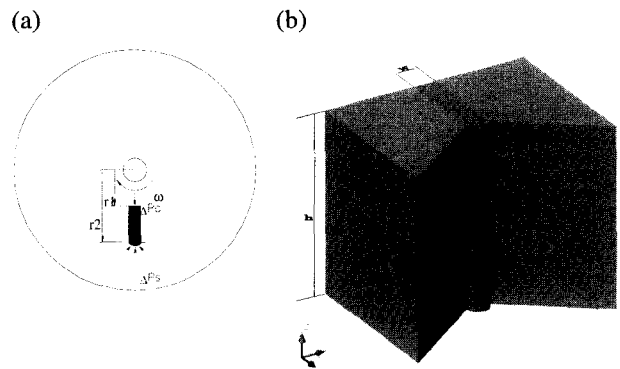


Fig. 1 (a) Centrifugal force on liquid in a microchannel. (b) A schematic of a rectangular channel with a capillary burst valve.

2.2 Pressure Difference across the Liquid Meniscus

The pressure difference across the liquid meniscus, ΔP_s is given by the Young-Laplace equation:

$$\Delta P_s = P_i - P_o = \sigma (1/R_1 + 1/R_2) \quad (1)$$

where P_i and P_o respectively denote the pressure inside and outside the liquid interface, and R_1 and R_2 are the principal radii of curvature. In a liquid channel, the radii of curvature are determined by the dimensions of the channel and the

* Microsystem Research Center, Korea Institute of Science and Technology (hscho@kist.re.kr).

** Microsystem Research Center, Korea Institute of Science and Technology (tskim@kist.re.kr), corresponding author.

*** Thermal/Flow Control Research Center, Korea Institute of Science and Technology (hoyoung@kist.re.kr).

contact angle. Geometric considerations yield the following relation for the pressure difference in a straight channel:

$$\Delta P_s = -2\sigma \cos\theta_A (1/h + 1/w) \quad (2)$$

where σ is the surface tension, θ_A is the advancing contact angle, and w and h denote the width and the height of the channel, respectively. Here we assume that the advancing contact angle is determined by the liquid/solid combination and is fairly insensitive to the speed of contact line. To drive liquid flow inside a hydrophobic microchannel, where ΔP_s is positive, external pressure should be applied to overcome such static pressure barrier and also viscous dissipation related to the liquid velocity.

A liquid flow through a microchannel can be regulated by devising an abruptly widening cross-section in the channel as shown in Fig. 1 (b). This area is called a capillary burst valve. The valve stops a liquid flow by pinning the contact line at the valve edge. The pinning takes place since the contact angle increases until its value with respect to the new surface reaches the critical advancing angle. Then the pressure profile can be obtained by using foregoing geometric considerations and the Young-Laplace relation. The analysis indicates that the pressure difference occurring at the pinned state is

$$\Delta P_s = -2\sigma (\cos\theta_A / h + \cos\theta_i / w) \quad (3)$$

where θ_i is the intermediate contact angle that varies between θ_A and $\theta_A + \beta$ as the liquid meniscus bends toward the open area. Here β is the diverging angle of the valve with respect to the straight channel as indicated in Fig. 1 (a). When the driving pressure exceeds the value of Eq. (3), the valve bursts and the static analysis provides the following relation for ΔP_s :

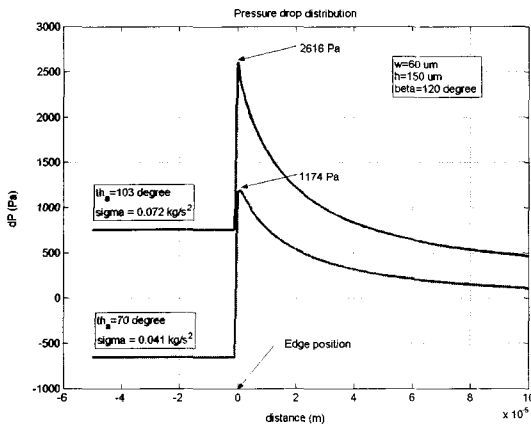


Fig. 2 Pressure difference across the liquid meniscus.

$$\Delta P_s = -2\sigma [\cos\theta_A / h + \cos\theta_i / 2b] \quad (4)$$

where θ_i equals θ_i when ΔP_s is a maximum value. Fig. 2 plots ΔP_s as the interface advances through the capillary burst valve, using Eqs. (2) - (4).

3. Numerical Simulations

To investigate the temporal evolution of liquid interface at the valve area, a numerical analysis was performed for two-dimensional channels. The channels were composed of two straight lines, which met abruptly where the valve diverges. Numerical simulations were conducted using commercial software, CoventorWare™. The conditions of the simulations are summarized in Table 1. The simulation results, i.e. the temporal profiles of the advancing interface, are shown in Fig. 3. The figure reveals that the meniscus shapes and wetting are different depending on the value of θ_A and β .

Table 1 Simulation conditions

θ_A		σ	ρ
120°	60°	7.2e-2 kg/s ²	998 kg/m ³

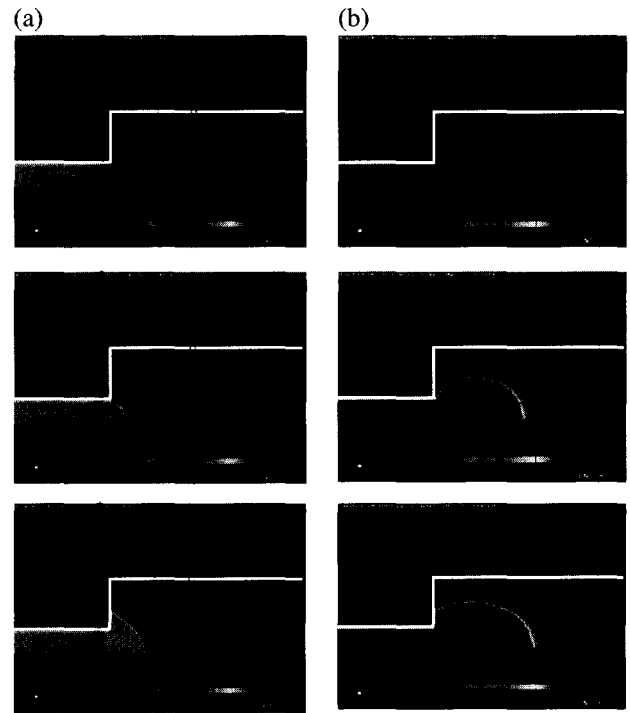


Fig. 3 Evolution of the interface near bursting for $\beta = 90^\circ$ cases, (a) hydrophilic fluid and (b) hydrophobic fluid. (upper: before pinning, middle: pinned and bursting, bottom: after bursting)

4. Experimental Study

4.1 Design of Valves

The valve stops the liquid flow when the maximum value of ΔP_s given by Eq. (3) exceeds the driving pressure of ΔP_c given by Eq. (5). Therefore, the performance of the valve is determined by h , w , θ_A and β . The bursting pressure can be experimentally investigated by changing the rotational speed for a given liquid. The dimensions of the valves designed for this work are listed in Table 2.

Table 2 Dimensions of the valves used in this work

h	w	β		
150 μm	60 μm	60°	90°	120°

4.2 Fabrication Processes

The channels were fabricated by a plastic molding process to decrease time and cost of fabrication. The primary mold was made of a photoresistor (SU-8). The photoresistor was spin-coated with a thickness of 150 μm and patterned using a conventional photolithography technique. Care was taken during the baking processes to prevent the photoresistor from undergoing rapid temperature fluctuation and minimizing thermal stress. The thermal stress tends to be concentrated at the opening edge of the valve, eventually deforming the microstructure. The opening edge of the valve was observed with a scanning electron microscope (S4200, Hitachi) to ensure that no thermal stress deformation had occurred. The results are compared in Fig. 4.

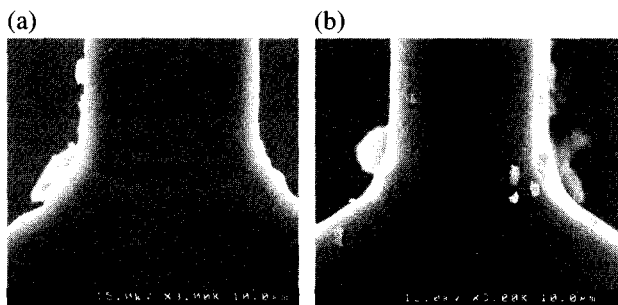


Fig. 4 Edge shape of SU-8 mold. (a) Normal heat treatment. (b) Careful heat treatment.

PDMS was then cast against the mold to yield an electrometric replica. The replication process is illustrated in Fig. 5 (a). The PDMS replica was bonded to a PC (polycarbonate) substrate. For the bonding, the substrate was coated with 1 μm thick Primer 1200 (Dow Corning),

which was then cured for 1 hour at room temperature. On the coating, a low-viscosity PDMS solution was spin-coated to a thickness of 10 μm . The replica and the coated substrate were bonded by curing the PDMS coating for 1 hour at 80°C. This process is shown in Fig. 5 (b). The upper channel and the lower substrate are bonded together and presented in Fig. 5 (c). The image of the processed wafer is presented in Fig. 6.

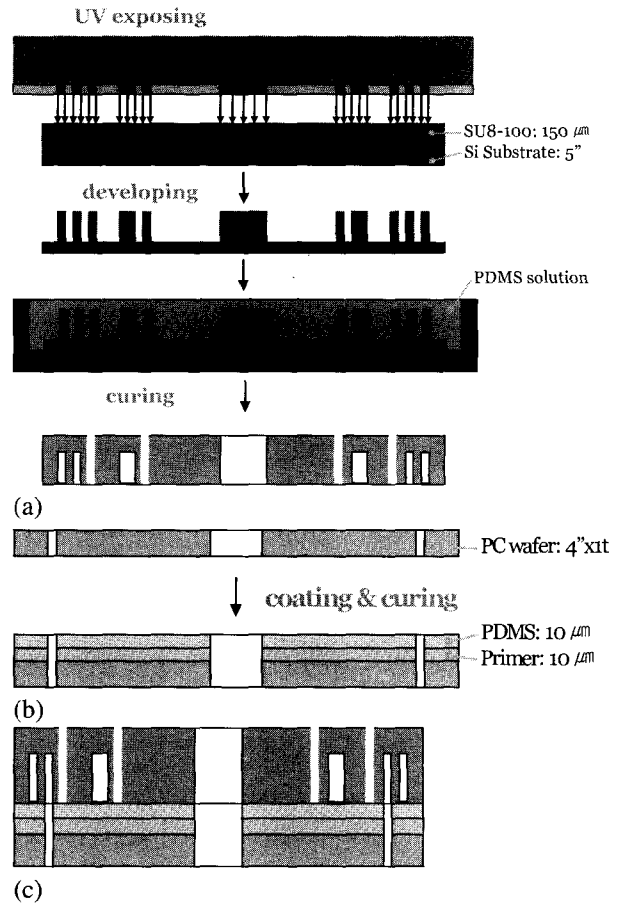


Fig. 5 Fabrication processes for (a) PDMS channel (b) PC substrate and (c) bonded chip

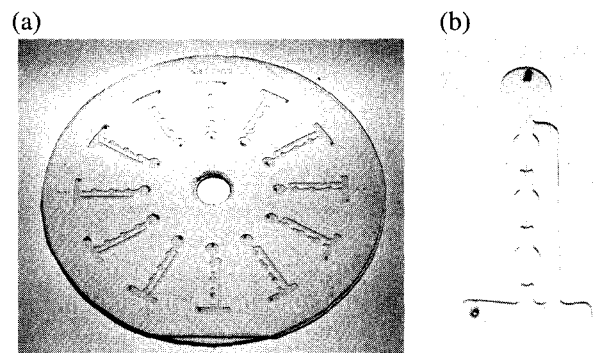


Fig. 6 Images of the processed wafer. (a) The entire wafer. (b) Enlarged section.

4.3 Experimental Procedure

The experimental apparatus is shown in Fig. 7. The system rotates a wafer with an AC servo motor controlled by an A/D converter, whose rotational speed ranges between 10 and 10,000 rpm. A CCD (charge coupled device) camera takes images of the rotating wafer in situ using a trigger signal synchronized with a counter connected to a frame grabber. The frame rate ranges between 15 and 30 frames per second and the exposure time can be reduced to 1.25 μ s.

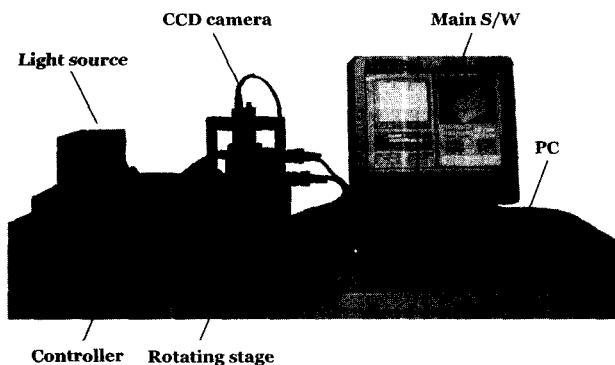


Fig. 7 A schematic of the centrifugal microfluidic system

The liquid used here is a water-dye (Phenol Red) mixture having physical properties as listed in Table 3. The microchannel wafer was loaded with a liquid volume of about 50 μ l. The sample chamber was completely filled with 20 μ l of the liquid, and the surplus was bypassed into a waste channel. By rotating the wafer, the liquid filling the sample chamber was driven to flow through a channel. At low rotating speeds, the flow was stopped at the valve. However, by gradually increasing the rotating speed, a critical pressure difference that caused the valve to burst was obtained.

Table 3 Physical properties of the liquid

θ_A	σ	ρ
95°	0.058 kg/s ²	1018.5 kg/m ³

4.4 Experimental Results

Experimental images of liquid flow around the valve are shown in Fig. 8. The images appear similar to the results obtained by the numerical simulations as discussed above. To compare the experimental measurements of the bursting pressure with our theoretical predictions, tests were performed using valves with different diverging angles, β . Fig. 9 reveals that the experimental results and the theoretical predictions are in good agreement.

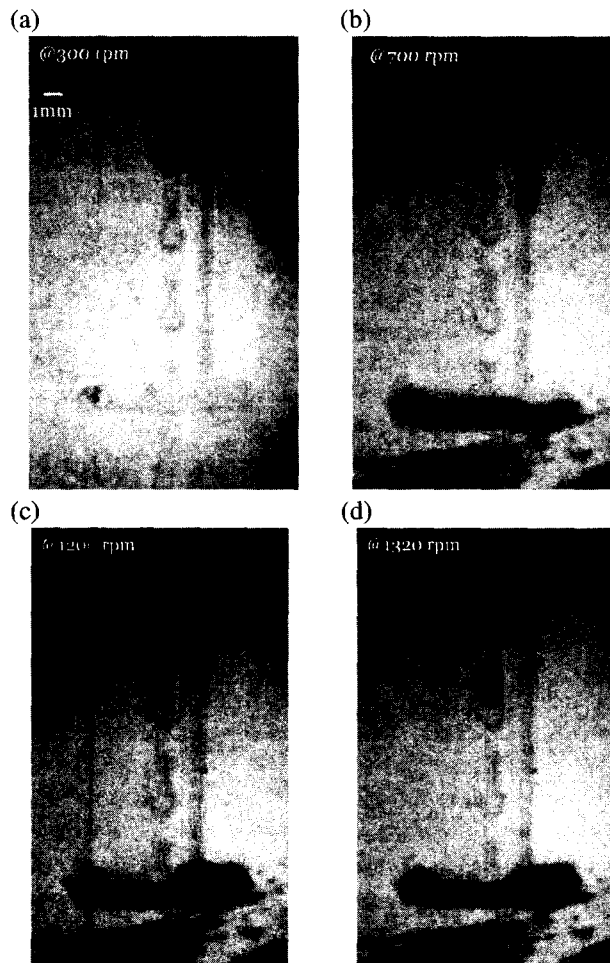


Fig. 8 Experimental images of the liquid around the valve. (a) Sample loading (b) Before pinning (c) Pinning (d) After bursting

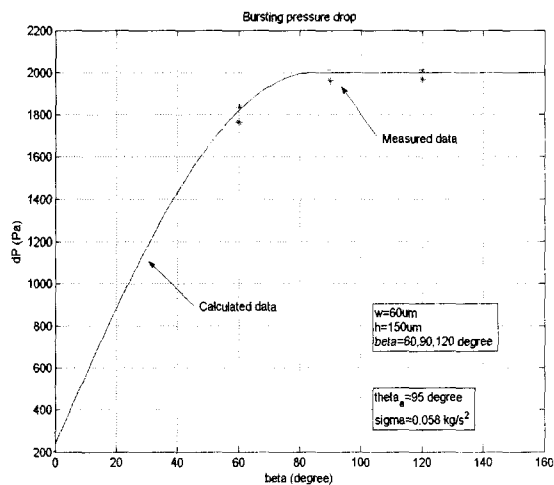


Fig. 9 Theoretical prediction of bursting pressure and experimental measurements.

5. Conclusions

Capillary burst valves provide beneficial means to regulate microscale liquid channel flows since they involve no moving parts and are easy to fabricate. In particular, a wafer-rotation system can easily achieve flow regulation by adjusting rotation speed according to the critical bursting pressure of the valve. This work investigated the pressure difference that the capillary burst valve can withstand depending on the liquid properties and channel dimensions. We provided a rigorous theoretical formulation that predicts the pressure difference developing around the liquid meniscus. Numerical simulations were performed to show the meniscus shape evolution while the interface was pinned. Furthermore, a microfluidic valve and rotational wafer system were fabricated to test the performance of the capillary burst valves. The valve operation was visualized by a triggered video system. The experiments indicated that the measurement results and the theoretical predictions were in good agreement.

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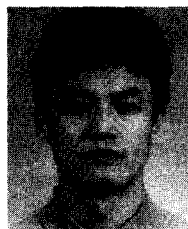
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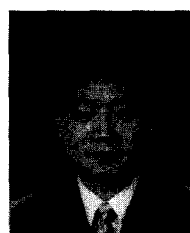
Han-Sang Cho

He received his B.S. and M.S. degrees in Mechanical Design and Production Engineering from Seoul National University, Korea in 1996 and 1998 respectively. His research interests are microfluidics, bio sensing chip, and cellular fluidic dynamics.



Ho-Young Kim

He received his B.S. (1994) degree from Seoul National University, Korea, and the S.M. (1996) and Ph.D. (1999) degrees from the Massachusetts Institute of Technology, Cambridge, MA, all in mechanical engineering. His research interest centers on microfluidics and interfacial flow physics.



Ji-Yoon Kang

He received his B.S. (1990), M.S. (1992) and Ph.D. (1997) degrees in Mechanical Design and Production Engineering from Seoul National University, Korea. His research interests are microfluidics, BioMEMS, BioSensor/ Chip, and piezoelectric MEMS devices.



Seung-Min Kwak

He received his B.S. degree in Mechanical Design and Automation Engineering from Seoul National University of Technology, Korea in 2001. His research interests are microfluidics and micro injection molding.



Tae-Song Kim

He is a Principal Research Scientist, Director of Microsystem Research Center, Korea Institute of Science and Technology (KIST). He received his B.S. degree in Electronic Material and Devices from Yonsei University, Korea in 1982, and M.S. and Ph.D. in Material Science and Engineering from Korea Advanced Institute of Science and Technology (KAIST), Korea in 1984 and 1993. He joined the department of electrical and computer science engineering, Univ. of Minnesota, USA as a postdoctoral associate for the study of MEMS (Micro Electro Mechanical System) devices from 1997 to 1998. His research activities have been focused on the Bio MEMS, BioSensor/Chip and piezoelectric MEMS devices.