

# Design of shrinkage microvalve in microchannel with hydrophilic and hydrophobic walls

Ping Zhang · Yongbo Deng · Yongshun Liu ·  
Yihui Wu

Received: 6 March 2011 / Accepted: 3 August 2011 / Published online: 17 August 2011  
© Springer-Verlag 2011

**Abstract** This paper presents a simple design of shrinkage microvalves which can be used to effectively stopping capillary flow inside a microchannel with hydrophilic and hydrophobic walls. Based on the relationship between capillary pressure and cross-section geometry of a microchannel, the microvalve is designed with a critical ratio of rectangular section. In order to verify the feasibility of the design rule, a couple of shrinkage microvalves with different aspect ratios of cross-section are fabricated by using PDMS bonded with glass wafer. The experiment demonstrates the stopping effect of the proposed design of shrinkage microvalve.

## 1 Introduction

The microfluidic chip has provided a platform to conduct chemical and biochemical analysis in a miniaturised format. Miniaturised analysis has various advantages such as

fast analysis time, small reagent consumption, and less waste generation. In addition, it has the capability of integration of sample preparation and further analysis (Li 2005). By using microchannels as the network connexions, microfluidic chips integrate microfluidic components, such as micropump (Laser and Santiago 2004), microvalve (Oh and Ahn 2006), micromixer (Nguyen and Wu 2005) etc., to achieve sampling, processing, delivering, metering, and mixing for biochemical analysis. For the raw materials of microfluidic chip, the silicon, glass and polymeric material PDMS and PMMA, have been widely used because of the low cost and simple fabricating process. Among the above mentioned microfluidic components, microvalves which are used to stop microflows, is one of the most important microfluidic components. Microvalves can be categorised as the active and passive types (Oh and Ahn 2006). An active microvalve is designed with moving parts so that it needs to pay attention to integration. On the contrary, a passive microvalve is designed based on the geometric shape or surface property of microchannels. Therefore, a passive microvalve has the characteristics about simple fabrication and integration process, and has been widely used in microfluidic chips. Capillary valve which works based on the theory of contact angle hysteresis (Shikhmurzaev 2008), is a typical passive microvalve. When the liquid flows on the surface of solid substrate, the physical defect of solid surface causes the anchoring effect on the three-phase (gas, liquid and solid) contact line, and then the stopping of the capillary flow is realised. Furthermore, the conventional capillary valve can be categorised as the hydrophobic valves which stop the capillary flow by a hydrophobic area (Feng et al. 2003; Andersson et al. 2001; Madou et al. 2006), and expansion valves which stop the capillary flow by a size-extension of the cross-section inside microchannels (Cho et al. 2007;

P. Zhang · Y. Deng · Y. Liu · Y. Wu  
State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP), Chinese Academy of Sciences, Changchun 130033, China

P. Zhang (✉) · Y. Liu · Y. Wu (✉)  
Suzhou Institute of Biomedical Engineering and Technology,  
Chinese Academy of Sciences, Suzhou 215163, China  
e-mail: zhangpingres@hotmail.com

Y. Wu  
e-mail: yihuiwu@ciomp.ac.cn

Y. Deng · Y. Liu  
Graduate University of Chinese Academy of Sciences,  
Beijing, China

Leu and Chang 2004; Gliere and Delattre 2006). For a spontaneous capillary, there are two ways for bursting capillary valves, i.e., the driven pressure (Cho et al. 2007; Chen et al. 2008; Man et al. 1998) and liquid–liquid triggered ways (Melin et al. 2004). The hydrophobic valve needs hydrophobic treatment inside microchannels, which complicates the fabrication processing. The expansion valve realises the stopping of capillary flow through the size-expansion of microchannel, which may occur invalidity due to the dynamic effect of the capillary flow (Gliere and Delattre 2006). In this paper, a design for microvalve is proposed to stop spontaneous capillary by setting a width-shrinkage section in the microchannel with hydrophilic and hydrophobic walls. The shrinkage microvalve overcomes the drawback of complicated process of a hydrophobic valve and offers higher reliability than the expansion valve. In Sect. 2, the design theory of the shrinkage microvalve is presented. In Sect. 3, the designed microvalves are fabricated with PDMS and glass; and the experimental data are discussed in Sect. 4.

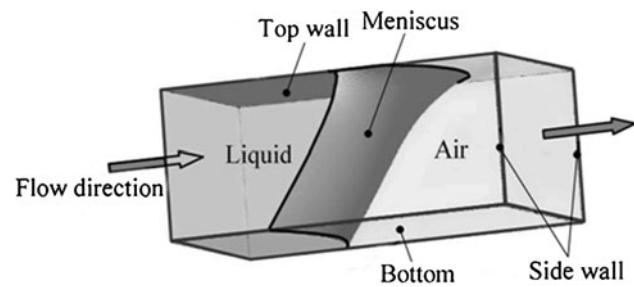
## 2 Design theory

In this paper, microvalves which are used to stop the capillary flow are limited to be a piece of microchannel with rectangular cross-section, and the walls of microvalve are formed with specific hydrophilic and hydrophobic properties. The capillary in such microchannels is pulled by hydrophilic walls which overcome the resistance of the hydrophobic walls. Capillarity means the spontaneous movement of liquids based on cohesive forces within the liquid and adhesive forces between the liquid and its surroundings (Jokinen and Franssila 2008). The microcosmic forces are presented by the capillary pressure, which is defined as the difference of the pressure between the liquid side and air side of the capillary meniscus. Therefore, the spontaneous capillary occurs when the capillary pressure satisfies (Cho et al. 2007)

$$\Delta p > 0 \quad (1)$$

where  $\Delta p = p_l - p_a$  is the capillary pressure;  $p_l$  and  $p_a$  are the pressure at the liquid and air sides of the capillary meniscus, respectively (Fig. 1).

On the contrary, the ongoing capillary phenomenon can be broke in the section of the microchannel, where the capillary pressure dissatisfies Eq. 1, i.e., the pulling of the hydrophilic walls is restrained by the resistance of the hydrophobic walls. For a rectangular microchannel where the side walls are hydrophobic and at least one of the top and bottom walls is hydrophilic (Fig. 2), the capillary pressure on the meniscus (Fig. 1) can be expressed as (Kim and Whitesides 1997; Jokinen and Franssila 2008)



**Fig. 1** The schematic of the capillary meniscus in a microchannel with hydrophilic and hydrophobic walls

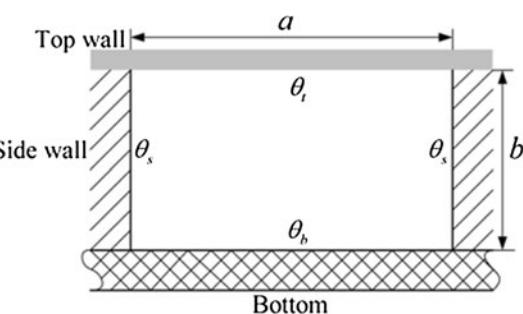
$$\Delta p = \gamma \left( \frac{\cos \theta_t + \cos \theta_b}{b} + 2 \frac{\cos \theta_s}{a} \right) \quad (2)$$

where  $\gamma$  is the surface tension of the liquid;  $a$  and  $b$  are the width and depth of the channel;  $\theta_t$ ,  $\theta_s$  and  $\theta_b$  are the contact angles of the liquid on the top wall, side wall and bottom of the microchannel, respectively (Fig. 2);  $\lambda = b/a$  is the aspect ratio of the microchannel.

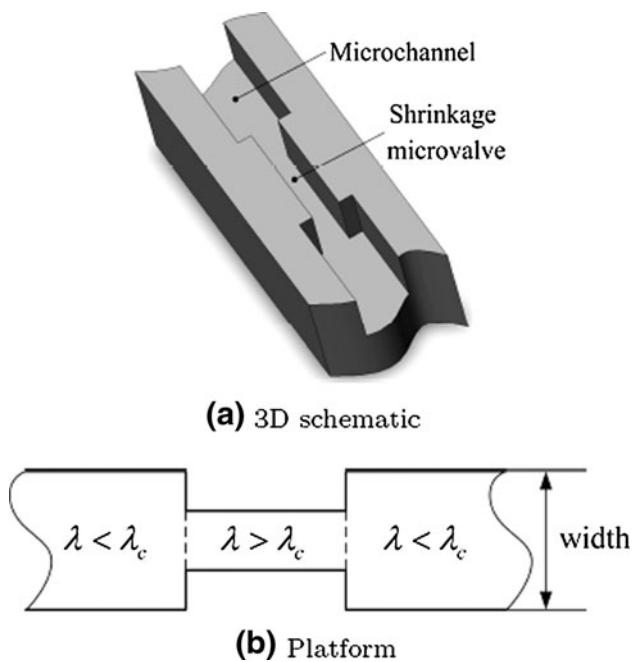
Because the side walls are hydrophobic, the contact angle satisfies  $\theta_s > 90^\circ$ . According to Eq. 2, one can obtain the critical aspect ratio of the microchannel with hydrophilic and hydrophobic walls for the spontaneous capillary as

$$\lambda_c = - \frac{\cos \theta_t + \cos \theta_b}{2 \cos \theta_s} \quad (3)$$

where  $\lambda_c$  is the critical aspect ratio. When  $\lambda < \lambda_c$  is satisfied, the spontaneous capillary occurs; otherwise, the capillary is restrained. Naturally, a microvalve can be located in certain place where the critical aspect ratio of microchannel's cross-section satisfies  $\lambda > \lambda_c$ . For the case that the depth of the whole microchannel is identical, a microvalve to stop the spontaneous capillary flow can be designed by shrinking the width of some section of the microchannel (Fig. 3), and is named as *shrinkage microvalve* in this paper. The burst of a stopped capillary flow by the shrinkage microvalve can be achieved by imposing an extra pressure on the liquid side to ensure the capillary



**Fig. 2** The cross-section of the rectangular microchannel with hydrophilic and hydrophobic walls.  $a$  and  $b$  are the width and depth of the channel;  $\theta_t$ ,  $\theta_s$  and  $\theta_b$  are the contact angles of the liquid on the top wall, side wall and bottom of the channel, respectively



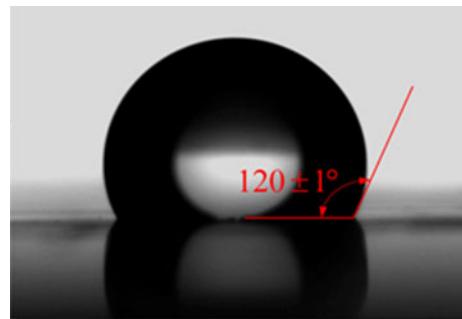
**Fig. 3** Schematic of a shrinkage microvalve formed by shrinking the width of microchannel

pressure  $\Delta p \geq 0$ . Therefore, the burst pressure  $p_b$  for a shrinkage microvalve can be evaluated as  $p_b = -\Delta p$ .

### 3 Experiments

To confirm the validity of the shrinkage microvalve designed by the theory in Sect. 2, several shrinkage microvalves with different aspect ratios are fabricated in the microchannels, which ensure the spontaneous capillary except the sections taken up by the shrinkage microvalves. The liquid is chosen as water. The microstructures are moulded using PDMS and the microchannels are formed by three PDMS walls and one glass wall. The measured contact angle of water on PDMS is  $120 \pm 1^\circ$  on temperature  $20^\circ\text{C}$ , humidity  $45 \sim 50 \text{ g/m}^3$  and normal atmospheric pressure (Fig. 4).

The glass is processed by oxygen plasma treating (treating time 20 min), and bonded with PDMS immediately. The stopping effect of capillary flow at the shrinkage microvalve is verified after the fabrication of microvalve. Therefore, it is assumed that the glass wall is completely hydrophilic and the contact angle of water on the treated glass wafer is  $0^\circ$ . Based on the above datum of contact angles, one can see that the bottom and side walls of the microchannels are hydrophobic, while the top wall is hydrophilic. According to Eq. 3, the critical aspect ratio of the fabricated microchannels is in the range of  $0.47 \sim 0.53$ . Therefore, the depth and width of the microchannels can be chosen as 200 and  $800 \mu\text{m}$  (aspect ratio

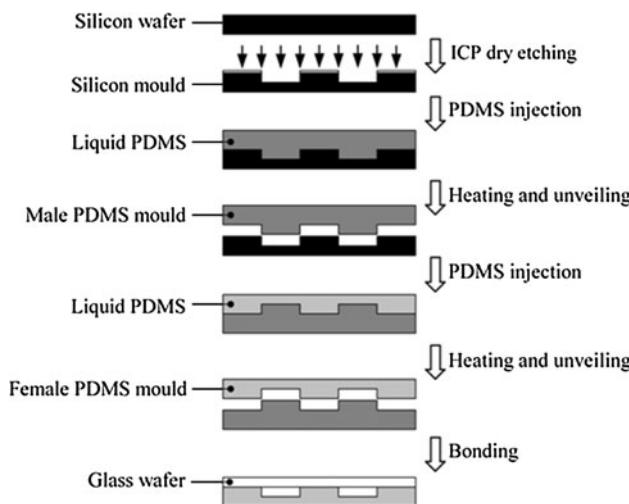


**Fig. 4** Contact angle of water drop on PDMS surface

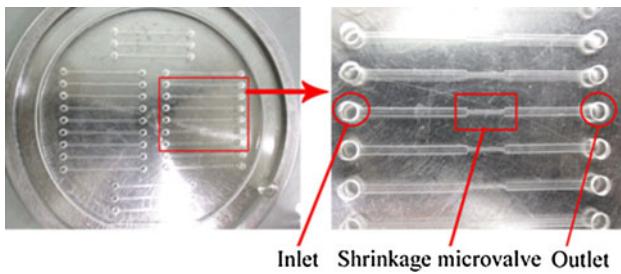
$0.25$ ) in order to ensure that the aspect ratio of microchannels is lower than the critical value. In order to compare the performance of the shrinkage microvalve, several shrinkage microvalves are fabricated with width in the range  $200 \sim 440 \mu\text{m}$  and the corresponding aspect ratios in the range of  $0.45 \sim 1.00$ .

The fabrication of microvalves are illustrated in Fig. 5 with following steps: (a) the silicon mould is obtained by ICP dry etching process; (b) after mixed with ratio 10:1 and degasification, the bi-component Sylgard 184 PDMS is injected on the silicon mould, then heated at  $120^\circ\text{C}$  to cure for 15 min; (c) the solidified male PDMS mould is unveiled from the silicon mould; (d) the mixed PDMS is injected on the male PDMS mould, then heated at  $120^\circ\text{C}$  to cure for another 15 min; (e) the solidified female PDMS mould is unveiled from the male PDMS mould; (f) two vents are drilled at both ends of the grooves in the female PDMS mould, then the female PDMS mould is bonded with the treated glass wafer based on the sticky property of the PDMS surface, and the shrinkage microvalves in microchannels is obtained (Fig. 6). After obtaining the shrinkage microvalves, water is injected from the inlets of the microchannels for the validation of the design.

In experiments, the Sylgard 184 PDMS is produced by American Dow Corning Corporation; the glass wafer is chosen as the round glass sheet with diameter of 76 mm; the thickness of the polished silicon wafer is  $380 \mu\text{m}$ . The contact angle of water on PDMS surface is measured by Drop Shape Analysis System DSA100 produced by KRUSS Company of Germany. Before the ICP dry etching of the silicon wafer, the photolithographic process is performed by the EVG 101 glue sprayer, KarSussHP8 heating platen and KarSuss MA6/BA6 phototeching machine. The ICP dry etching of silicon wafer is carried out by the Alcatel 601E ICP. The degasification of the mixed PDMS is performed by DZF-6050 vacuum baking-oven. The experimental results are recorded by MEIJI EMZ-TR stereoscopic microscope, Union DH2/IMH non-contact depth measurement microscope and Nikon Coolpix 4500 CCD camera. All the experiments, including the measurement of the contact angle, are carried out in the environment with



**Fig. 5** The fabricating progress of the microchannels

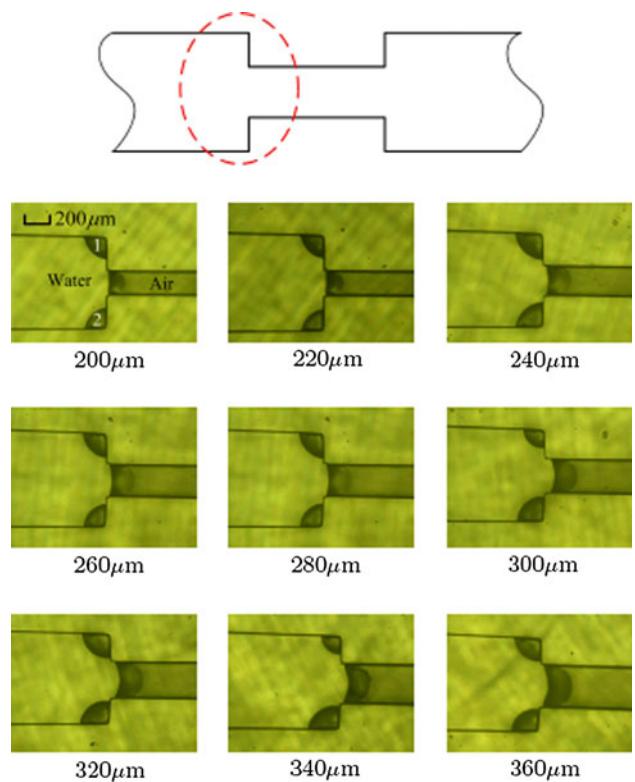


**Fig. 6** The shrinkage microvalves fabricated by bonding PDMS with glass

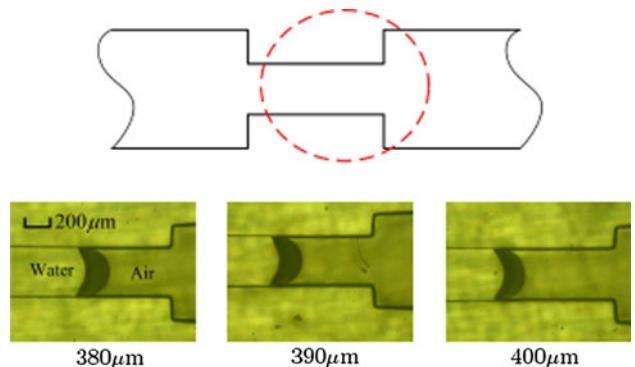
temperature 20°C humidity 45 ~ 50 g/m<sup>3</sup> and normal atmospheric pressure.

#### 4 Results and discussion

The microchannels, fabricated by bonding PDMS with glass wafer in Sect. 3, are formed by three hydrophobic walls and one hydrophilic wall. After dropping water into the inlets, the spontaneous capillary occurred immediately for all the fabricated microchannels. When the front of the capillary flow arrived at the shrinkage microvalves, the capillary flow is stopped at the threshold of the shrinking section with width in the range 200 ~ 360 μm (Fig. 7), and inside the shrinking section with width in 380 ~ 400 μm (Fig. 8), respectively. When the width of the shrinking section increases close to the critical value, the resistance of hydrophobic walls decreases and the pull of the hydrophilic wall increases. Therefore, the dynamic effect of the capillary flow becomes more powerful and results in the stopping inside the shrinking section (Fig. 8). The results in the shrinkage microvalves with width in 420 ~ 440 μm are shown in Fig. 9, where the capillary flow break through the shrinking section, because the

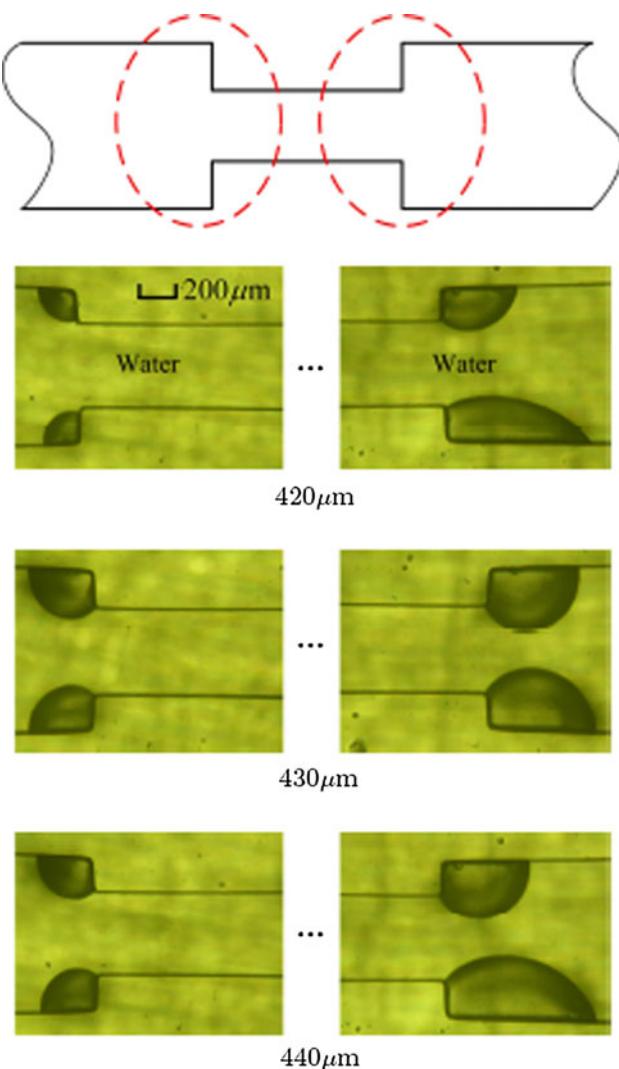


**Fig. 7** The stopping of the capillary flow at the threshold of the shrinking section. In the corners 1 and 2 shown in the figures, there are two air regions formed by the air



**Fig. 8** The stopping of the capillary flow mid the shrinking section

aspect ratio is lower than the critical value and the spontaneous capillary flow occurs in the shrinking section. Based on the results shown in Figs. 7, 8 and 9, one can conclude that the critical width of the shrinkage microvalve is between 400 and 420 μm. Therefore, for the shrinkage microvalve fabricated by bonding PDMS with glass wafer, the critical aspect ratio is in the range 0.50 ~ 0.52, which locates in the range of 0.47 ~ 0.53 obtained by theoretical computation based on the measured contact angle of water. Therefore, the experiments have a good agreement with the design theory presented in Sect. 2.



**Fig. 9** The powerless stopping of the capillary flow in the shrinking section

In Figs. 7 and 9, two air bubble regions exist in the place where the width of microchannel has abrupt changes. Because the capillary pressure at liquid–gas interfaces of the air regions is balanced by the pressure of the compressed air in the closed corners, the air regions have no influence on the stopping of the capillary flow in the shrinkage microvalve.

## 5 Conclusion

In this study, a shrinkage microvalve is proposed for the stopping of the capillary flow in the microchannel with hydrophilic and hydrophobic walls, and it has experimentally

demonstrated the stopping effect. The theoretical derivation of critical aspect ratio can serve as a general design rule for designing microvalves in microchannels with hydrophilic and hydrophobic walls. Because the contact angle of liquid may change with the environmental factors, it deserves to extend the current design rule to consider the effect of temperature, atmospheric pressure and other environment factors.

**Acknowledgments** This work is supported by the National High Technology Research and Development Programme (863 Program) of China (2007AA042102); China National Science fund (No. 50975272).

## References

- Andersson H, Wijngaart W, Griss P, Niklaus F, Stemme G (2001) Hydrophobic valves of plasma deposited octafluorocyclobutane in DRIE channels. *Sens. Actuators B* 75:136–141
- Chen JM, Huang PC, Lin MG (2008) Analysis and experiment of capillary valves for microfluidics on a rotating disk. *Microfluid Nanofluid* 4:427–437
- Cho H, Kim HY, Kang JY, Kim TS (2007) How the capillary burst microvalve works. *J Colloid Interf Sci* 306:379–385
- Feng Y, Zhou Z, Ye X, Xiong J (2003) Passive valves based on hydrophobic microfluidics. *Sens. Actuators A* 108:138–143
- Gliere A, Delattre C (2006) Modeling and fabrication of capillary stop valves for planar microfluidic systems. *Sens. Actuators A* 130–131:601–608
- Jokinen V, Franssila S (2008) Capillary in microfluidic channels with hydrophilic and hydrophobic walls. *Microfluid Nanofluid* 5:443–448
- Kim E, Whitesides GM (1997) Imbibition and flow of wetting liquids in noncircular capillaries. *J Phys Chem B* 101:855–863
- Kung CF, Chiu CF, Chen CF, Chang CC, Chu CC (2009) Blood flow driven by surface tension in a microchannel. *Microfluid Nanofluid* 6:693–697
- Laser DJ, Santiago JG (2004) A review of micropumps. *J Micromech Microeng* 14:35–64
- Leu TS, Chang PY (2004) Pressure barrier of capillary stop valves in microsample separators. *Sens. Actuators A* 115:508–515
- Li PCH (2005) Microfluidic lab-on-a-chip for chemical and biological analysis and discovery. CRC, Boca Raton
- Madou M, Zoval J, Jia G, Kido H (2006) Lab on a CD. *Annu Rev Biomed Eng* 8:601–628
- Man PF, Mastrangelo CH, Burns MA, Burke DT (1998) Microfabricated capillary driven stop valves and simple injector, in: MEMS Conference, Heidelberg, Germany, January 25–29
- Melin J, Roxhed N, Gimenez G, Griss P, Wijngaard W, Stemme G (2004) A liquid-triggered liquid microvalve for on-chip flow control. *Sens. Actuators B* 100:463–468
- Nguyen NT, Wu Z (2005) Micromixer—a review. *J Micromech Microeng* 15:1–16
- Oh KW, Ahn CH (2006) A review of microvalves. *J Micromech Microeng* 16:13–39
- Shikhamraev YD (2008) Capillary flow with forming interface. CRC, Cleveland