

# Multiphase flow in lab on chip devices: A real tool for the future?†

DOI: 10.1039/b808974b

## Introduction

Many applications for lab on a chip (LOC) devices require the use of two or more fluids that are either not chemically related (*e.g.* oil and water) or in different phases (*e.g.* liquid and gas). Utilizing multiphase flow in LOC devices allows for both the fundamental study of multiphase flow and the development of novel types of pumping, mixing, reaction, separation, and detection technologies. Current examples of multiphase microfluidics applications include inkjet printers,<sup>1–5</sup> separation of biochemical samples,<sup>6</sup> manipulation of biomolecules,<sup>7</sup> bio-sensing,<sup>8</sup> enhanced mixing for bio-sample reactions,<sup>9,10</sup> biomolecule detection,<sup>11</sup> microelectronic cooling,<sup>12</sup> drug delivery devices,<sup>13,14</sup> explosives detection,<sup>15</sup> dairy analysis,<sup>16–18</sup> bubble computing<sup>19</sup> and analysis of emulsions, foams, and bubble coalescence.<sup>20</sup> In this focus article, we will briefly review the basics of multiphase flow with reference to microfluidic systems, describe some of the most promising flow control methods for multiphase fluid systems, and discuss our thoughts about future directions of microfluidic multiphase flow.

## Interfacial forces and the capillary number

Multiphase flow can be loosely defined as the flow of immiscible fluids in one device. Therefore, an interface will be present, which implies various intermolecular forces acting on the interface, characterized by the interfacial tension. The interface may also intersect a solid boundary at a contact line. The contact angle at this line is a determining factor for the shape of the interface. Thus, variation of either the interfacial tension or the contact angle varies the forces on the bulk phases, and these forces may be manipulated and

controlled. For a better overview of interfacial forces at the micro-scale, the authors refer you to ref. 21 and 23 for excellent reviews and articles about the theory of multiphase flow in microchannels.

Typically, the dominant forces at the micro-scale are viscous forces and interfacial forces, which can be related through a dimensionless parameter called the capillary number,  $Ca$ . Viscous forces act tangentially to a phase boundary and elongate the boundary, whereas interfacial forces act normal to the interface, inducing a droplet or bubble to minimize the interfacial area.<sup>24,25</sup> As an example, when different phases are injected as adjacent streams in one channel, one phase often preferentially wets the boundaries and encapsulates the second fluid as discrete droplets due to the high interfacial forces at the microscale.<sup>24,26–30</sup> However, a stable interface can also be generated between two phases by modifying forces on the channels and fluids.<sup>30–33</sup> The capillary number is a convenient nondimensional parameter that can be used to describe the ratio of viscous and interfacial force across a phase boundary, and it is this ratio that controls the flow pattern of the two phases. The capillary number is defined as:

$$Ca = \frac{\mu v}{\gamma}, \quad (1)$$

where  $\mu$  and  $v$  are the continuous phase viscosity and velocity, respectively, and  $\gamma$  is the interfacial tension between the fluids. Low capillary numbers indicate the domination of interfacial forces, and therefore droplet-based flow, as shown in Fig. 1(a). Conversely, high capillary numbers indicate high viscous forces that tend to elongate the phase boundaries, eventually leading to stratified flow (Fig. 1(b)). Note that it is not the capillary number alone that determines the stratification/segmentation of the flow, it also depends on the flow rates and viscosities of the different fluids, as well as the geometry of the microfluidic device.<sup>25, 30,32,34–38</sup>

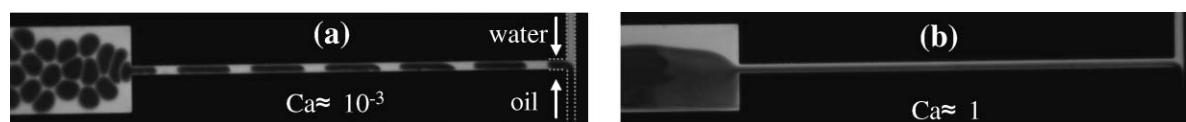
## Examples of microfluidic multiphase flows

Workhorse flow control methods, such as pressure-driven and to a much lesser extent electroosmotic flow, are still the dominant methods to drive multiphase flow in microfluidics.<sup>22</sup> However, as we scale a system down, interfacial forces become predominant. Therefore, at the microscale it is promising to drive flows using interfacial tension driven flow control methods, such as electrowetting and passive micropumping. This section will explain the mechanisms for various types of multiphase flows in microfluidic devices.

**Pressure-driven flow.** Pressure-driven flow can drive fluids over a broad range of velocities and pressures, and is suitable for any phase and medium of fluid, and therefore is a workhorse flow control method for micro- and nanofluidics. Pressure-driven multiphase flow systems in microfluidic devices have been used for particle synthesis, reactions, droplet coalescence studies, and other interfacial phenomena studies.<sup>32,39–48</sup> Although it is an extremely robust and well-characterized type of flow, the pressures needed to drive fluid increase as the system decreases in size, diminishing the practicality of the flow control system. Additionally, pressure-driven flow systems generally require macro-scale components, and so it is difficult to create a truly portable LOC system.

**Electroosmotic flow (EOF).** EOF, the other workhorse flow of LOC devices, is most commonly used for driving electrolyte fluids through channels by the application of an axial electric field. In general, this type of flow is not used in multiphase systems, since one of the phases is usually either a conductor (*e.g.* metal particles) or an insulator (*e.g.* oil). However, in microfluidic systems with a stationary solid phase and a conductive liquid phase, EOF can be used to drive

† The HTML version of this article has been enhanced with colour images.



**Fig. 1** Effect of  $Ca$  on microfluidic flow patterns of oil and water. In both (a) and (b), the microfluidic channels are  $10\ \mu\text{m}$  high and  $10\ \mu\text{m}$  wide. The oil phase is hexadecane (dark) and water phase (white) is seeded with  $0.01\ \text{M}$  fluorescein sodium salt.  $Ca$  is varied by changing  $\gamma$  while keeping all other variables constant (flow rate ratio, viscosity ratio). The surfactants used to change the oil/water interfacial tension are sodium dodecyl sulfate (SDS) (in water) and Span80 (in oil).

the liquid through the system. Examples of solid–liquid systems using EOF as a flow control method include micro fuel cells<sup>49–51</sup> and solid phase extraction (SPE) electrochromatography.<sup>52</sup>

**Interfacial tension driven flow.** Intermolecular forces between different phases can induce fluid movement. Driving fluids using interfacial forces is ideal for multiphase microfluidics since there is a large surface area to volume ratio. A gradient in interfacial tension can induce fluidic movement, generating flows such as Marangoni flows. Interfacial tension also gives rise to phenomena such as wetting and passive pumping; however in these cases the interfacial tension leads to gradients of pressure which in turn drive the flow. In this section, we will detail a few flow control methods of microfluidic multiphase flow that require interfacial tension.

**Marangoni flow.** Marangoni flow is a result of gradients in interfacial tension along a free surface (*i.e.* a liquid surface in contact with air), which produces a tangential stress. This stress must be equilibrated by a viscous stress due to flow and thus gradients in interfacial tension set the interface into motion. The most common microfluidic Marangoni flow is caused by thermal gradients<sup>53–57</sup> applied to the device. Theoretical and experimental studies of this kind of flow includes microfluidic flows along hydrophilic strips,<sup>54,56</sup> as well as thermocapillary bubble motion through capillaries.<sup>55,57</sup> Applications of this sort of fluidic control method include droplet motion and liquid spreading.<sup>53</sup> In general, there are several advantages for thermo-driven Marangoni flow: (1) there can be exquisite control of temperature gradients due to the application of electric fields, or lasers, (2) the power consumption is low, which make a battery-powered system possible, and (3) such a system can be built so that it is bio-compatible. Disadvantages include: (1) the difficulty of *locally* controlling temperature, since

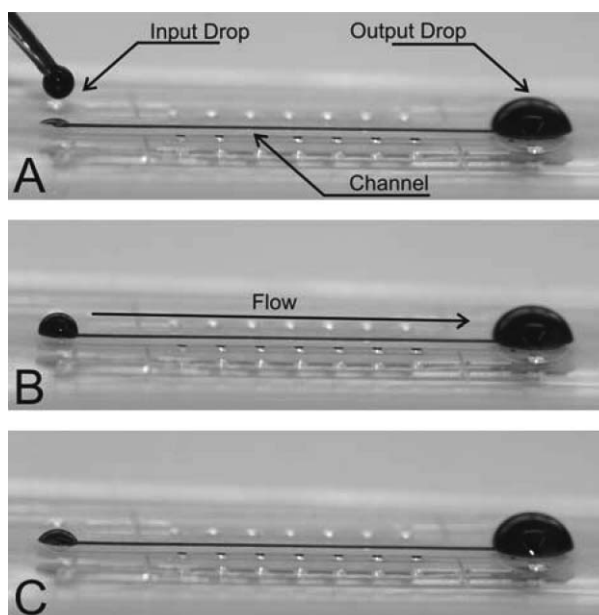
different surfaces have different local thermal conductivities and (2) the difficulty of manipulating the fluids which have very low boiling points and low interfacial tension temperature coefficients.

**Passive micropumping.** In contrast to Marangoni flows, passive micropumping occurs because of interfacial tension induced pressure differences in different size droplets connected *via* a microchannel (see Fig. 2). In general, the pressure in the droplets is due to an interfacial tension induced pressure drop and a hydrostatic pressure drop.<sup>58–60</sup> However as the radius of the drop is decreased, the pressure due to interfacial tension becomes much larger than the hydrostatic pressure. Note that the dimensionless number that measures this effect is the Bond number, and using this number we find that any droplet smaller than about  $3\ \text{mm}$  is unaffected by gravity.<sup>10</sup> Therefore, in microfluidic flows, the total pressure drop mimics that of the Young–Laplace equation and is inversely proportional to the radius of the droplet:

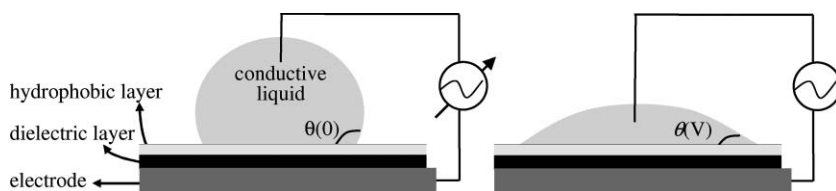
$$\Delta P_{\text{surface tension}} = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (2)$$

where  $\Delta P$  is the difference between atmospheric pressure and the pressure inside the drop,  $R_1$  and  $R_2$  are the radii of curvature for two axes normal to each other that describe the curvature of the surface. Consequently, the smaller radius of curvature of the smaller droplet will create a larger pressure inside the drop. Therefore, two drops of different size connected *via* a fluid filled channel will induce a pressure gradient across the channel and fluid will flow from the small drop to the larger drop. An experimental demonstration of an interfacial-tension driven, passive micropump is shown in Fig. 2.<sup>58,59</sup> In addition, passive pumping has been used in combination with electrocapillarity in ref. 61 and 62 to develop a low dissipation micro-switch.

**Electrowetting.** Electrowetting can be described as the change in the contact angle or interfacial tension due to an applied



**Fig. 2** Passive pumping chip containing a small input drop and a large output drop. (A) Before placement of drop. (B) and (C) During the flow. Reprinted from ref. 63 with permission from RSC publishing.



**Fig. 3** Schematic of electrowetting device. Note that the droplet is placed on both a hydrophobic layer and dielectric layer, to ensure a high contact angle when zero voltage is applied, and to allow for high voltages to be applied without breakdown.

potential difference between a solid and an electrolyte, and the resulting flow is called electrocapillary flow.<sup>64–70</sup> Electrowetting of a fluid in contact with a conductor tends to cause electrochemical reactions and Joule heating, diminishing the utility of the device.<sup>71</sup> Therefore, electrowetting generally occurs on a dielectric (electrowetting on a dielectric, EWOD).<sup>64,66,67,72–80</sup> Fig. 3 shows a typical microfluidic electrowetting device, including an electrode, an insulating layer and hydrophobic layer. The hydrophobic layer ensures a high contact angle when zero voltage is applied, and the dielectric allows for high voltages to be applied without breakdown.

The driving mechanism for the motion of a liquid droplet in an electrowetting field is the change in contact angle of the droplet. This change induces a change in the curvature and pressure between the front and the back (see eqn (2)). Therefore, the flow is driven by wettability, rather than by interfacial tension gradients. The droplet moves toward higher voltages because the contact angle decreases with voltage, as shown in Fig. 4. Electrowetting has been used to manipulate droplets or film flow,<sup>64,76–79</sup> to form droplets,<sup>81</sup> for mixing,<sup>78,82</sup> to manipulate surface patterns,<sup>83</sup> microvalve<sup>74</sup> and fluid focus lens. This phenomenon has also created a field of study in microfluidics called “digital microfluidics”,<sup>84–86</sup> where microfluidic processing is performed on droplets of fluid which can be transported, stored, mixed, reacted or analyzed using a

set of basic instructions. As discussed in a previous focus article<sup>22</sup> advantages of this method of driving flow include (1) the application of high potentials without electrochemical reactions and (2) repeatable flow due to clean surfaces. Disadvantages include (1) lower capacitance requires a stronger applied potential to achieve a given contact angle change, and (2) biomolecules tend to nonspecifically adsorb to the surface typically used in these studies.<sup>87</sup>

### A viable tool for the future?

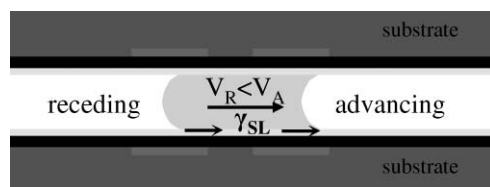
Over the past 10 years multiphase microfluidics has been a steadily growing field. The question is, whether this field will grow, plateau, or decay over time. Given the plethora of applications for multiphase microfluidic flow and the increase of analytical, theoretical, and computation methods for solving multiphase flows, we believe that the field will not only continue to grow, but may even experience an exponential growth as robust theory is developed to describe experimental results. In this section, we will describe these thoughts in more detail and explain why we believe multiphase flow will be not only a viable tool, but also a necessary one in the future.

We think that multiphase microfluidics will have large impact towards solving biological problems. This is due to the fact that biological systems are inherently multiphase systems. Multiphase LOC devices

have the potential to affect the biological field in many different ways. A few examples of ways we can develop LOC devices for biology are to (1) mimic biological systems to study biological mechanisms *in vitro*, (2) implant in living organisms for drug delivery, implantable organs, tissues, and other systems, and vitals monitoring, and (3) be used as bioanalytical tools (separation, mixing, *etc.*). Finally, fundamental knowledge of microfluidic interfacial phenomenon may elucidate biological mechanisms and allow us to probe more complex biological systems and pathways.

As device size decreases, the importance of interfacial tension-driven flows will rise dramatically. Pressure-driven flow will be extremely difficult due to the large pressure gradients required. Conversely, the increase of surface area to volume ratio in nanoscale channels may allow for increased control of interfacially-driven flows. The few existing studies on multiphase flows at the nanoscale<sup>88</sup> allude to the importance of interfacial tension and wettability, especially when compared to applied pressure gradients. Other reasons that multiphase flow will be popular at the nanoscale include the small residence time, fast thermal transfer, and absence of hydrodynamic dispersion. Therefore, nanofluidic multiphase flow may allow for ideal 2D nano-reactors, mixers, and separators.

Currently, multiphase flow in microfluidics is exploited for a variety of applications, including emulsification and encapsulation, microreaction, synthesis, micromixing, bioassay, cell assay and protein crystallization. These studies are still in a nascent stage, and therefore we can expect a steady growth of this field towards such applications. It is interesting to note there are many theoretical and computational studies of multiphase flow primarily found in the fluid mechanics and physics literature, which tend to focus on basic phenomena in simple and well-characterized geometries. However many of the studies in the microfluidics literature are application-driven experimental studies involving complex geometries and little or no theory. We hope that as the microfluidic community continues to use multiphase systems for such applications, the two communities will work together to elucidate complex microfluidic multiphase flows. A resulting growth of multiphase microfluidics can be expected, since not



**Fig. 4** Driving flow through microfluidic channels using electrowetting. The solid–liquid interfacial tension change is described by  $\Delta\gamma_{SL} = (\epsilon_0\epsilon_r/2\lambda)(V_A^2 - V_R^2)$ , where  $V_A$  and  $V_R$  are applied voltages at the advancing and receding sides, respectively,  $\epsilon_0\epsilon_r$  the dielectric constant, and  $\lambda$  the dielectric layer thickness. Flow moves from left to right, due to  $V_A > V_R$ , inducing a lower contact angle at the advancing side, and thus a lower interfacial tension.

only can these studies be used for the ubiquitous microfluidic applications, but they can also be used to probe the fundamental physics of interfacial phenomena for all (micro- and macro-scale) applications.

#### Lingling Shui

BIOS/Lab-on-a Chip group  
MESA+ Institute of Nanotechnology  
University of Twente  
The Netherlands  
l.shui@ewi.utwente.nl

#### Sumita Pennathur

Department of Mechanical  
Engineering  
University of California, Santa Barbara  
USA  
sumita@engineering.ucsb.edu

#### Jan C. T. Eijkel

BIOS/Lab-on-a Chip group  
MESA+ Institute of Nanotechnology  
University of Twente  
The Netherlands

#### Albert van den Berg

BIOS/Lab-on-a Chip group  
MESA+ Institute of Nanotechnology  
University of Twente  
The Netherlands

## Acknowledgements

The authors would like to kindly acknowledge Prof. G. M. Homsy for all his generous advice and guidance.

## References

- 1 Y. Ishida, K. Sogabe, K. Haklai, A. Baba and T. Asano, Properties of ink-droplet formation in double-gate electrospray, *Jpn. J. Appl. Phys., Part 1*, 2006, **45**(8A), 6475–6480.
- 2 D. B. van Dam and C. Le Clerc, Experimental study of the impact of an ink-jet printed droplet on a solid substrate, *Phys. Fluids*, 2004, **16**(9), 3403–3414.
- 3 G. Percin and B. T. Khuri-Yakub, Micromachined droplet ejector arrays for controlled ink-jet printing and deposition, *Rev. Sci. Instrum.*, 2002, **73**(5), 2193–2196.
- 4 L. Palm and J. Nilsson, Impact on droplet placement on paper bit the level of droplet flight stability in a continuous ink jet printer, *J. Imaging Sci. Technol.*, 1998, **42**(6), 534–540.
- 5 A. Badea, C. Carasso and G. Panasencko, A model of a homogenized cavity corresponding to a multinozzle droplet generator for continuous ink-jet printers, *Numer. Methods Partial Differential Equations*, 1998, **14**(6), 821–842.
- 6 T. Fujimura *et al.*, Fabrication of open-top microchannel plate using deep X-ray exposure mask made with silicon on insulator substrate, *Jpn. J. Appl. Phys., Part 1*, 2003, **42**(6B), 4102–4106.
- 7 Y. C. LoC.-S. Hung W. Hsu and C. Wang, Neural guidance by open-top SU-8 microfluidic channel in *Proceedings of the 2004 international conference on MEMS, NANO and Smart System (ICMENS 2004)*, IEEE Explore, pp. 671–674.
- 8 K. G. Wang *et al.*, Manipulating DNA molecules in nanofluidic channels, *Microfluidics Nanofluidics*, 2006, **2**(1), 85–88.
- 9 I. D. Yang, Y. F. Chen, F. G. Tseng, H. T. Hsu and C. C. Chieng, Surface tension driven and 3-D vortex enhanced rapid mixing microchamber, *J. Microelectromech. Syst.*, 2006, **15**(3), 659–670.
- 10 H. A. Stone, A. D. Stroock and A. Ajdari, Engineering flows in small devices: Microfluidics toward a lab-on-a-chip, *Annu. Rev. Fluid Mech.*, 2004, **36**, 381–411.
- 11 F. G. Tseng, K. H. Lin, H. T. Hsu and C. C. Chieng, A surface-tension-driven fluidic network for precise enzyme batch-dispensing and glucose detection, *Sens. Actuators, A*, 2004, **111**(1), 107–117.
- 12 R. H. Nilson, S. W. Tchikanda, S. K. Griffiths and M. Martinez, Steady evaporating flow in rectangular microchannels, *Int. J. Heat Mass Transfer*, 2006, **49**(910), 1603–1618.
- 13 K. B. Neeves, C. T. Lo, C. P. Foley, W. M. Saltzman and W. L. Olbricht, Fabrication and characterization of microfluidic probes for convection enhanced drug delivery, *J. Controlled Release*, 2006, **111**(3), 252–262.
- 14 A. J. Chung, D. Kim and D. Erickson, Electrokinetic microfluidic devices for rapid, low power drug delivery in autonomous microsystems, *Lab Chip*, 2008, **8**(2), 330–338.
- 15 B. D. Piorek, S. J. Lee, J. G. Santiago, M. Moskovits, S. Banerjee and C. D. Meinhart, Free-surface microfluidic control of surface-enhanced Raman spectroscopy for the optimized detection of airborne molecules, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**(48), 18898–18901.
- 16 O. Skurtys and J. M. Aguilera, Applications of microfluidic devices in food engineering, *Food Biophys.*, 2008, **3**(1), 1–15.
- 17 G. Monti, L. De Napoli, P. Mainolfi, R. Barone, M. Guida, G. Moreno and A. Amoresano, Monitoring food quality by microfluidic electrophoresis, gas chromatography, and mass spectrometry techniques: Effects of aquaculture on the sea bass (*Dicentrarchus labrax*), *Anal. Chem.*, 2005, **77**(8), 2587–2594.
- 18 A. G. Crevillen, M. Avila, M. Pumera, M. C. Gonzalez and A. Escarpa, Food analysis on microfluidic devices using ultrasensitive carbon nanotubes detectors, *Anal. Chem.*, 2007, **79**(19), 7408–7415.
- 19 M. Prakash and N. Gershenfeld, Microfluidic bubble logic, *Science*, 2007, **315**(5813), 832–835.
- 20 J. G. Kralj, M. A. Schmidt and K. F. Jensen, Surfactant-enhanced liquid–liquid extraction in microfluidic channels with in-line electric-field enhanced coalescence, *Lab Chip*, 2005, **5**(5), 531–535.
- 21 T. M. Squires and S. R. Quake, Microfluidics: Fluid physics at the nanoliter scale, *Rev. Mod. Phys.*, 2005, **77**(3), 977–1026.
- 22 S. Pennathur, Flow control in microfluidics: are the workhorse flows adequate?, *Lab Chip*, 2008, **8**(3), 383–387.
- 23 L. Shui, J. C. T. Eijkel and A. van den Berg, Multiphase flow in micro- and nanochannels, *Sens. Actuators, B*, 2007, **121**(1), 263.
- 24 M. Joanicot and A. Ajdari, Droplet control for microfluidics, *Science*, 2005, **309**(5736), 887–888.
- 25 V. Reddy and J. D. Zahn, Interfacial stabilization of organic-aqueous two-phase microflows for a miniaturized DNA extraction module, *J. Colloid Interface Sci.*, 2005, **286**(1), 158–165.
- 26 A. S. Utada, E. Lorenceau, D. R. Link, P. D. Kaplan, H. A. Stone and D. A. Weitz, Monodisperse double emulsions generated from a microcapillary device, *Science*, 2005, **308**(5721), 537–541.
- 27 T. Kawakatsu, G. Tragardh, C. Tragardh, M. Nakajima, N. Oda and T. Yonemoto, The effect of the hydrophobicity of microchannels and components in water and oil phases on droplet formation in microchannel water-in-oil emulsification, *Colloids Surf., A*, 2001, **179**(1), 29–37.
- 28 I. G. Loscertales, A. Barrero, I. Guerrero, R. Cortijo, M. Marquez and A. M. Ganan-Calvo, Micro/nano encapsulation via electrified coaxial liquid jets, *Science*, 2002, **295**(5560), 1695–1698.
- 29 J. D. Tice, H. Song, A. D. Lyon and R. F. Ismagilov, Formation of droplets and mixing in multiphase microfluidics at low values of the Reynolds and the capillary numbers, *Langmuir*, 2003, **19**(22), 9127–9133.
- 30 B. Zheng, J. D. Tice and R. F. Ismagilov, Formation of droplets in microfluidic channels alternating composition and applications to indexing of concentrations in droplet-based assays, *Anal. Chem.*, 2004, **76**(17), 4977–4982.
- 31 H. Hisamoto, T. Saito, M. Tokeshi, A. Hibara and T. Kitamori, Fast and high conversion phase-transfer synthesis exploiting the liquid–liquid interface formed in a microchannel chip, *Chem. Commun.*, 2001, (24), 2662–2663.
- 32 M. W. Losey, R. J. Jackman, S. L. Firebaugh, M. A. Schmidt and K. F. Jensen, Design and fabrication of microfluidic devices for multiphase mixing and reaction, *J. Microelectromech. Syst.*, 2002, **11**(6), 709–717.
- 33 B. Zheng and R. F. Ismagilov, A microfluidic approach for screening submicroliter volumes against multiple reagents by using preformed arrays of nanoliter plugs in a three-phase liquid/liquid/gas flow, *Angew. Chem. Int. Ed.*, 2005, **44**(17), 2520–2523.
- 34 S. T. Thoroddsen and Y. K. Tan, Free-surface entrainment into a rimming flow containing surfactants, *Phys. Fluids*, 2004, **16**(2), L13–L16.
- 35 A. Serizawa, Z. Feng and Z. Kawara, Two-phase flow in microchannels, *Exp. Therm. Fluid Sci.*, 2002, **26**(6–7), 703–717.
- 36 A. Gunther, S. A. Khan, M. Thalmann, F. Trachsel and K. F. Jensen, Transport and reaction in microscale segmented gas-liquid flow, *Lab Chip*, 2004, **4**(4), 278–286.
- 37 D. Huh, Y. C. Tung, H. H. Wei, J. B. Grotberg, S. J. Skerlos, K. Kurabayashi and S. Takayama, Use of air-liquid two-phase flow in hydrophobic microfluidic channels for disposable flow cytometers, *Biomed. Microdevices*, 2002, **4**(2), 141–149.

- 38 L. Shui, J. C. T. Eijkel and A. van den Berg, Multiphase flow in microfluidic systems—Control and applications of droplets and interfaces, *Adv. Colloid Interface Sci.*, 2007, **133**(1), 35.
- 39 S. A. Khan, A. Gunther, M. A. Schmidt and K. F. Jensen, Microfluidic synthesis of colloidal silica, *Langmuir*, 2004, **20**(20), 8604–8611.
- 40 B. Regenber, M. Simon, J. Nielsen, U. Krühne, M. Beyer, L. H. Pedersen, O. R. T. Thomas and T. Ahl, Use of laminar flow patterning for miniaturised biochemical assays, *Lab Chip*, 2004, **4**(6), 654–657.
- 41 K. Ueno, F. Kitagawa and N. Kitamura, Photocyanation of pyrene across an oil/water interface in a polymer microchannel chip, *Lab Chip*, 2002, **2**(4), 231–234.
- 42 T. Tokimoto, S. Tsukahara and H. Watarai, Lactone cleavage reaction kinetics of rhodamine dye at liquid/liquid interfaces studied by micro-two-phase sheath flow two-photon excitation fluorescence microscopy, *Langmuir*, 2005, **21**(4), 1299–1304.
- 43 T. Tokimoto, S. Tsukahara and H. Watarai, Kinetic study of fast complexation of zinc(II) with 8-quinolinol and 5-octyloxymethyl-8-quinolinol at 1-butanol/water interface by two-phase sheath flow/laser-induced fluorescence microscopy, *Bull. Chem. Soc. Jpn.*, 2003, **76**(8), 1569–1576.
- 44 S. Pautot, B. J. Frisken, J. H. Cheng, X. S. Xie and D. A. Weitz, Spontaneous formation of lipid structures at oil/water lipid interfaces, *Langmuir*, 2003, **19**(24), 10281–10287.
- 45 H. Z. Wang, H. Nakamura, M. Uehara, M. Miyazaki and H. Maeda, Preparation of titania particles utilizing the insoluble phase interface in a microchannel reactor, *Chem. Commun.*, 2002, (14), 1462–1463.
- 46 A. Hibara, M. Nonaka, H. Hisamoto, K. Uchiyama, Y. Kikutani, M. Tokeshi and T. Kitamori, Stabilization of liquid interface and control of two-phase confluence and separation in glass microchips by utilizing octadecylsilane modification of microchannels, *Anal. Chem.*, 2002, **74**(7), 1724–1728.
- 47 C. L. Hansen, S. R. Quake, E. Skordalakest and J. M. Berger, A robust and scalable microfluidic metering method that allows protein crystal growth by free interface diffusion, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**(26), 16531–16536.
- 48 R. Pit, H. Hervet and L. Léger, Direct experimental evidence of slip in hexadecane: solid interfaces, *Phys. Rev. Lett.*, 2000, **85**(5), 980–983.
- 49 L. Jiang, J. Mikkelsen, J.-M. Koo, D. Huber, S. Yao, L. Zhang, P. Zhou, J. G. Maveety, R. Prasher, J. G. Santiago, T. W. Kenny and K. E. Goodson, Closed-Loop Electroosmotic Microchannel Cooling System for VLSI Circuits, *IEEE Trans. Compon. Packag. Manuf. Technol.*, 2002, **25**(3), 347–355.
- 50 E. R. Choban, P. J. A. Kenis, L. J. Markoski and A. Wiczkowski, Microfluidic fuel cell based on laminar flow, *J. Power Sources*, 2004, **128**(1), 54–60.
- 51 C. H. Hidrovo *et al.*, Two-phase microfluidics for semiconductor circuits and fuel cells, *Heat Transfer Eng.*, 2006, **27**(4), 53–63.
- 52 P. H. Choi, D. G. Bessarabov and R. Datta, A simple model for solid polymer electrolyte (SPE) water electrolysis, *Solid State Ionics*, 2004, **175**(1–4), 535–539.
- 53 V. G. Levich *Physicochemical Hydrodynamics*, 1962 Englewood Cliffs, NJ, Prentice-Hall.
- 54 A. Darhuber, J. Chen, J. Davis and S. Troian, *Philos. Trans. R. Soc. London, Ser. A*, 2004, **362**, 1037.
- 55 E. Lajeunesse and G. M. Homsy, *Phys. Fluids*, 2003, **15**, 308.
- 56 D. Kataoka and S. Troian, *Nature*, 1999, **402**(794).
- 57 A. Mazaouchi and G. M. Homsy, *Phys. Fluids*, 2001, **13**, 1594.
- 58 E. Berthier and D. J. Beebe, Flow rate analysis of a surface tension driven passive micropump, *Lab Chip*, 2007, **7**(11), 1475–1478.
- 59 G. M. Walker and D. J. Beebe, A passive pumping method for microfluidic devices, *Lab Chip*, 2002, **2**(3), 131–134.
- 60 J. C. T. Eijkel and A. van den Berg, Water in micro- and nanofluidics systems described using the water potential, *Lab Chip*, 2005, **5**, 1202–1209.
- 61 E. A. Theisen, M. J. Vogel, C. A. Lopez, A. H. Hirska and P. H. Steen, Capillary dynamics of coupled spherical-cap droplets, *J. Fluid Mech.*, 2007, **580**, 495–505.
- 62 A. H. Hirska, C. A. Lopez, M. A. Laytin, M. J. Vogel and P. H. Steen, Low-dissipation capillary switches at small scales, *Appl. Phys. Lett.*, 2005, **86**(1).
- 63 E. Berthier and D. J. Beebe, Flow Rate Analysis of a Surface Tension Driven Passive Micropump, *Lab Chip*, 2007, **7**(1475–1478), 1475–1478.
- 64 M. W. J. Prins, W. J. J. Welters and J. W. Weekamp, Fluid control in multichannel structures by electrocapillary pressure, *Science*, 2001, **291**(5502), 277–280.
- 65 C. J. Kim, Micropumping by electrowetting, *American Society of Mechanical Engineers, Heat Transfer Division, (Publication) HTD*, 2001, vol. 369, p. 62.
- 66 J. Lee, H. Moon, J. Fowler, T. Schoellhammer and C.-J. Kim, Electrowetting and electrowetting-on-dielectric for microscale liquid handling, *Sens. Actuators, A*, 2002, **95**(2–3), 259–268.
- 67 M. G. Pollack, A. D. Shenderov and R. B. Fair, Electrowetting-based actuation of droplets for integrated microfluidics, *Lab Chip*, 2002, **2**(2), 96–101.
- 68 H. Moon, S. K. Cho, R. L. Garrell and C. J. Kim, Low voltage electrowetting-on-dielectric, *J. Appl. Phys.*, 2002, **92**(7), 4080–4087.
- 69 W. J. J. Welters and L. G. J. Fokkink, Fast electrically switchable capillary effects, *Langmuir*, 1998, **14**(7), 1535–1538.
- 70 G. Beni and M. A. Tenan, Dynamics of Electrowetting Displays, *J. Appl. Phys.*, 1981, **52**(10), 6011.
- 71 W. Satoh, M. Loughran and H. Suzuki, Microfluidic transport based on direct electrowetting, *J. Appl. Phys.*, 2004, **96**(1), 835–841.
- 72 K. L. Wang and T. B. Jones, Electrowetting dynamics of microfluidic actuation, *Langmuir*, 2005, **21**(9), 4211–4217.
- 73 T. B. Jones, K. L. Wang and D. J. Yao, Frequency-dependent electromechanics of aqueous liquids: electrowetting and dielectrophoresis, *Langmuir*, 2004, **20**(7), 2813–8.
- 74 J. Y. Cheng and L. C. Hsiung, Electrowetting (EW)-based valve combined with hydrophilic Teflon microfluidic guidance in controlling continuous fluid flow, *Biomed. Microdevices*, 2004, **6**(4), 341–347.
- 75 A. R. Wheeler, H. Moon, C. J. Kim, J. A. Loo and R. L. Garrell, Electrowetting-based microfluidics for analysis of peptides and proteins by matrix-assisted laser desorption/ionization mass spectrometry, *Anal. Chem.*, 2004, **76**(16), 4833–4838.
- 76 D. Huh, A. H. Tkaczyk, J. H. Bahng, Y. Chang, H. H. Wei, J. B. Grothberg, C. J. Kim, K. Kurabayashi and S. Takayama, Reversible switching of high-speed air-liquid two-phase flows using electrowetting-assisted flow-pattern change, *J. Am. Chem. Soc.*, 2003, **125**(48), 14678–14679.
- 77 R. A. Hayes and B. J. Feenstra, Video-speed electronic paper based on electrowetting, *Nature*, 2003, **425**(6956), 383–5.
- 78 P. Paik, V. K. Pamula, M. G. Pollack and R. B. Fair, Electrowetting-based droplet mixers for microfluidic systems, *Lab Chip*, 2003, **3**(1), 28–33.
- 79 M. G. Pollack, R. B. Fair and A. D. Shenderov, Electrowetting-based actuation of liquid droplets for microfluidic applications, *Appl. Phys. Lett.*, 2000, **77**(11), 1725–1726.
- 80 H. Moon, S. Cho, R. Garrell and C. J. Kim, *J. Appl. Phys.*, 2002, **92**, 4080.
- 81 F. Malloggi, S. A. Vanapalli, H. Gu, D. van den Ende and F. Mugele, Electrowetting-controlled droplet generation in a microfluidic flow-focusing device, *J. Phys.: Condens. Matter*, 2007, **19**(46).
- 82 F. Mugele, J. C. Baret and D. Steinhauser, Microfluidic mixing through electrowetting-induced droplet oscillations, *Appl. Phys. Lett.*, 2006, **88**(20).
- 83 A. Klingner and F. Mugele, Electrowetting-induced morphological transitions of fluid microstructures, *J. Appl. Phys.*, 2004, **95**(5), 2918–2920.
- 84 Sung Kwon Cho and Y. Z. a. C.-J. C. K., Concentration and binary separation of micro particles for droplet-based digital microfluidics, *Lab Chip*, 2007, **7**, 490–498.
- 85 V. K. P. Phil Paik, Michael G. Pollack and Richard B. Fair, Electrowetting-based droplet mixers for microfluidic systems, *Lab Chip*, 2003, **3**, 28–33.
- 86 R. B. Fair V. S. H. Ren, P. Paik, V. K. Pamula, M. G. Pollack, Electrowetting-based On-Chip Sample Processing for Integrated Microfluidics, in *IEEE Int. Electron Devices Meeting (IEDM)*, 2003.
- 87 T. Squires and S. R. Quake, Microfluidics: Fluid Physics at the nanoliter scale, *Rev. Mod. Phys.*, 2005, **77**(3), 977–1027.
- 88 L. Shui, S. Kooij, J. C. T. Eijkel and A. van den Berg, Liquid crystallography in nano- and microchannels, in *Twelfth International Conference on Miniaturized Systems for Chemistry and Life Sciences (Micro Total Analysis Systems-μTAS 2008)*, 2008, San Diego.