

# Droplet-based microfluidics with nonaqueous solvents and solutions†

Debalina Chatterjee,<sup>a</sup> Boonta Hetayothin,<sup>b</sup> Aaron R. Wheeler,<sup>b</sup> Daniel J. King<sup>b</sup> and Robin L. Garrell<sup>\*abc</sup>

Received 2nd November 2005, Accepted 1st December 2005

First published as an Advance Article on the web 9th January 2006

DOI: 10.1039/b515566e

In droplet-based (“digital”) microfluidics, liquid droplets in contact with dielectric surfaces are created, moved, merged and mixed by applying AC or DC potentials across electrodes patterned beneath the dielectric. We show for the first time that it is possible to manipulate droplets of organic solvents, ionic liquids, and aqueous surfactant solutions in air by these mechanisms using only modest voltages (<100 V) and frequencies (<10 kHz). The feasibility of moving any liquid can be predicted empirically from its frequency-dependent complex permittivity,  $\epsilon^*$ . The threshold for droplet actuation in air with our two-plate device configuration is  $|\epsilon^*| > 8 \times 10^{-11}$ . The mechanistic implications of these results are discussed, along with the greatly expanded range of applications for digital microfluidics that these results suggest are now feasible.

## Introduction and background

Microfluidics has emerged as a powerful tool for chemical and biological manipulations and assays. Benefits of microfluidics include reduced reagent consumption and analysis time, as well as the ability to integrate multiple functions onto a single device. In channel microfluidic devices, fluids are manipulated as continuous flows in micron-dimension channels.<sup>1</sup> In droplet-based (“digital”) microfluidic devices, a liquid is transported in the form of droplets on a planar array or between two parallel plates, rather than as a stream in a channel.<sup>2–4</sup> The two formats have complementary advantages; for example, channel microfluidic devices are particularly well suited for applications that involve separations,<sup>5</sup> while the digital microfluidics format marries naturally to applications that make use of arrays.<sup>6,7</sup> There are now several devices that make use of both motifs.<sup>8–10</sup>

Digital microfluidic devices typically rely on an array of electrodes buried beneath a hydrophobic dielectric layer. When potentials are applied to sequential electrodes, droplets can be made to move, merge, and split. Digital microfluidics has been implemented in a variety of geometries, including devices in which droplets are sandwiched between two electrode plates and moved in a matrix of air<sup>2–4</sup> or oil<sup>11–14</sup> and devices in which droplets are manipulated over a single array of electrodes while in contact with air<sup>15,16</sup> or oil.<sup>17–19</sup>

There is considerable debate about the mechanism(s) of droplet actuation in digital microfluidics. When a potential is applied across electrodes in a device, two phenomena may be observed: (1) a droplet may move towards the biased electrode, and (2) the contact angle between the droplet and device

surface may decrease; *i.e.*, the liquid may wet the surface. The latter phenomenon, essentially electrowetting, has been explained as arising from the accumulation of charge at the interface between the droplet and the surface,<sup>20–23</sup> polarization of the dielectric layer,<sup>24</sup> or line tension<sup>25</sup> or excess charge accumulation<sup>26</sup> at the three-phase line. The utilization of this effect to actuate droplets in digital microfluidic devices has been called “electrowetting-on-dielectric” (EWOD),<sup>2–4</sup> or simply, “electrowetting.”<sup>11–14</sup> Droplet movement has been modeled as a function of Laplace pressure,  $\Delta p$ :

$$\Delta p = \frac{\gamma_{LG}}{d} (\cos\theta_w - \cos\theta_s) \quad (1)$$

where  $\gamma_{LG}$  = liquid–gas surface tension,  $d$  = distance between top and bottom plates,  $\theta_w$  = wetted contact angle, and  $\theta_s$  = static (or initial) contact angle. According to this model, a liquid must be conductive and exhibit a significant electrically driven contact angle change in order to be movable.<sup>27</sup>

An alternative mechanism suggests that droplet motion results from dielectrophoresis (DEP).<sup>17–19,28–31</sup> In this mechanism, the nonconductive droplet and device dielectric layer comprise a capacitive voltage divider. Because the dielectric constants of the droplet and the suspending medium differ, a field gradient parallel to the driving electrodes is generated. This gradient gives rise to a DEP force that acts on aligned molecular dipoles within the droplet. The cumulative effect of this force actuates the macroscopic droplet. This phenomenon is analogous to electrohydrodynamic (EHD) pumping, which is used to transport streams of dielectric liquids in conductive channels.<sup>33–35</sup> According to the DEP model, the liquid must be an insulator or an imperfect conductor, and must have a dielectric constant greater than that of the suspending medium (*i.e.*, air or oil) in order to be movable.

Prior work had shown that droplets of water, buffers, protein solutions, and aqueous acetonitrile can be moved in digital microfluidic devices in air,<sup>6,7</sup> and that DMSO,<sup>36</sup> aqueous surfactants<sup>37</sup> and biological fluids<sup>38–41</sup> can be moved in oil. Our interest in using digital microfluidics in applications that include synthesis, biochemical assays requiring dissolution of proteins and cell lysis, biophysical assays such as enthalpy

<sup>a</sup>Biomedical Engineering Interdepartmental Program, University of California, Los Angeles, CA 90095-1569

<sup>b</sup>Department of Chemistry & Biochemistry, University of California, Los Angeles, CA 90095-1569

<sup>c</sup>California NanoSystems Institute. E-mail: garrell@chem.ucla.edu; Fax: +1 (310) 206-2061; Tel: +1 (310) 825-2496

† Electronic supplementary information (ESI) available: Movies of electrically driven movement of droplets of ethanol and chloroform, and splitting of an ethanol droplet. See DOI: 10.1039/b515566e

arrays, and array-based sensors, led us to assess the movability of other liquids and to deduce the physical properties that determine movability. A liquid is considered movable when it can be reversibly and repeatedly transported across three or more electrodes.

We report here that it is possible to use digital microfluidics to move and split droplets of pure organic solvents and solutions, ionic liquids and aqueous surfactant solutions in air. These liquids span a wide range of conductive and dielectric properties. We discuss the device parameters required for actuation, and propose that the complex permittivity of the liquid can be used to predict the feasibility of droplet movement.

## Experimental

### Reagents and materials

All test liquids were reagent grade or better. Cyclohexane, carbon tetrachloride, *m*-dichlorobenzene, toluene, chloroform, decane, formic acid, dibromomethane, tetrahydrofuran (THF), dichloromethane, 1-hexanol, 1-pentanol, ethanol, methanol, 4-methyl-3-heptanol, acetone, formamide, dimethylformamide (DMF), acetonitrile, dimethylsulfoxide (DMSO), sodium hydroxide, sodium dodecyl sulfate (SDS), HEPES, CHES, Triton X-100, Fluorinert FC-40, *p*-dichlorobenzene and tetra(*n*-butyl)ammonium tetrafluoroborate (TBATFB) were purchased from Aldrich (St. Louis, MO). Piperidine was from AnaSpec (San Jose, CA), 4-methyl-4-heptanol from TCI America (Portland, OR), butylmethylimidazolium hexafluorophosphate ([bmim]PF<sub>6</sub>) from Matrix Scientific (Columbia, SC), and butylmethylimidazolium tetrafluoroborate ([bmim]BF<sub>4</sub>) from Ryan Scientific (Isle Of Palms, SC).

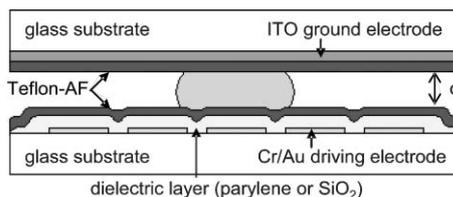
Stock solutions of HEPES (1 M, pH 7.4), SDS (10% w/v), and Triton X-100 were diluted with deionized (DI) water. Aqueous solutions of sodium phosphate (100 mM Na<sub>2</sub>HPO<sub>4</sub>, pH 7), sodium borate (100 mM boric acid, pH 9), potassium chloride (100 mM KCl) and CHES (100 mM, pH 9) were prepared in DI water and brought to pH with 1 N sodium hydroxide. Solutions of *p*-dichlorobenzene (saturated) and TBATFB (4.7 mM) in toluene were prepared.

Teflon-AF 1600 (DuPont, Wilmington, DE) stock solutions (6% w/v) were made in FC-40 (DuPont) and then diluted to 1.2% v/v with FC-40. Cleanroom reagents and supplies were used as provided by the UCLA Nanoelectronics Research Facility.

### Fabrication and use of devices

Devices were fabricated at the UCLA Nanoelectronics Research Facility and were similar to devices we have used in the past.<sup>2–4,6,7</sup> As depicted in Fig. 1, each device was formed from a bottom plate with individually addressable electrodes and a top plate fabricated as a single, large electrode.

The bottom plate was formed from a borofloat glass wafer purchased from Precision Glass and Optics (Santa Ana, CA). Chromium and gold electrodes were patterned by photolithography followed by wet etching. The electrodes were covered by a dielectric layer of parylene-C (9800 Å, chemical vapor deposition) or silicon dioxide (SiO<sub>2</sub>, 1.4 μm, plasma enhanced



**Fig. 1** Schematic of digital microfluidics device. The bottom plate is shown with an array of conductive electrodes, dielectric layer and hydrophobic Teflon-AF coating. The top plate has a single ITO electrode and Teflon-AF coating. The droplet is sandwiched between the two plates with spacing between plates, *d*.

chemical vapor deposition). Thin dielectric layers enable droplet actuation at very low applied potentials,<sup>3</sup> but we commonly observe electrolysis and bubble formation. We find that using a thick dielectric layer prevents electrolysis; bubble formation was not observed under any conditions for any of the devices used in this work.

On devices covered with silicon dioxide, the electrode contact pads were opened by photolithography followed by etching with buffered hydrofluoric acid; this step was unnecessary for the parylene devices, as parylene could be scratched away from the contact pads before testing. The devices were then primed with hexamethyldisilazane (HMDS, 5 min) vapor and spin-coated (2000 RPM, 60 s) with 1.2% Teflon-AF. The SiO<sub>2</sub> devices were post-baked on a hotplate (160 °C, 10 min) and in a furnace (330 °C, 30 min) to form a uniform ~500 Å layer of Teflon-AF. The parylene devices were post-baked on a hotplate at 110 °C for 5 min followed by 180 °C for 15 min.

The top plate was formed from indium tin oxide (ITO)-coated glass pieces (Delta Technologies, Ltd, Stillwater, MN). A ~500 Å layer of Teflon-AF was spin-coated onto the ITO coated glass and annealed as for the oxide devices. The two plates were joined with one, two, or three pieces of 3M double-sided tape, which formed spacers of ~100, 200, or 300 μm. For ~50 μm spacers, single-sided polyimide tape (Kapton tape, Bertech, Torrance, CA) was used.

Droplets (0.2–0.6 μL for moderate to high boiling point liquids and up to 2 μL for low boiling point liquids) were sandwiched between the two plates, and moved by applying 90 V<sub>rms</sub> AC potentials at 10 Hz–8 kHz between the electrode in the top plate and successive electrodes in the bottom plate.<sup>2–4,6,7</sup> Droplet movement was monitored and recorded with a CCD camera (GP-KR222 Panasonic, Secaucus, NJ) mated to an imaging lens (VZM 200i Edmund Industrial Optics, Barrington, NJ) positioned over the top of the device. For each liquid tested, at least three droplets were evaluated per device, and on several devices formed from both parylene and silicon dioxide. Droplet movement was found to be equally facile on devices formed from parylene and SiO<sub>2</sub>.

### Characterization of reagent properties

A contact angle goniometer (First Ten Ångströms, Portsmouth, VA) was used to assess voltage-induced contact angle changes in stationary droplets.<sup>42–44</sup> Unpatterned test substrates, formed from pieces of phosphorous doped silicon

wafer (WaferNet Inc., San Jose, CA) coated with PECVD oxide (1.4  $\mu\text{m}$ ) or parylene-C (9800  $\text{\AA}$ ) and Teflon-AF (500  $\text{\AA}$ ), were used for these measurements. To measure electrically-induced contact angle changes, a test substrate served as the bottom electrode and a 100  $\mu\text{m}$  diameter platinum wire (Aldrich, Milwaukee, WI) as the top electrode. The contact angles of 5  $\mu\text{L}$  DI water droplets were measured without and with AC potentials at 8 kHz. The voltage at which the contact angle change in water droplets was maximized (contact angle saturation)<sup>42–44</sup> was observed to be 75  $V_{\text{rms}}$ . Although several liquids were movable at 75  $V_{\text{rms}}$ , movement was more easily accomplished for all movable liquids at 90  $V_{\text{rms}}$ . We chose to keep the experimental voltage constant at 90  $V_{\text{rms}}$  so that we could identify the dominating liquid property or properties enabling droplet movement. AC potentials were applied because operations involving DC potentials are often limited by electrochemistry occurring on the electrodes (*e.g.*, irreversible reactions, oxidation, bubble generation due to electrolysis).<sup>45,46</sup> The conditions for all experiments, contact angle as well as experiments done on chip, were in the ranges of  $23.7 \pm 0.8$   $^{\circ}\text{C}$  and  $50 \pm 5\%$  relative humidity. The average and standard deviation of contact angle change measurements of at least five droplets of each liquid were recorded.

Contact angle change data did not depend on the AC frequency; the data presented are from parylene devices, as there were no significant differences between the contact angles measured on parylene and  $\text{SiO}_2$  devices.

For liquids with low boiling points, larger droplets were dispensed to compensate for the rapid rate of evaporation. Goniometer measurements of static contact angle over time for low boiling point liquids showed negligible change (*e.g.*,  $\pm 0.4^{\circ}$  for dichloromethane, b.p. 40  $^{\circ}\text{C}$ , and  $\pm 1.7^{\circ}$  for chloroform, b.p. 61  $^{\circ}\text{C}$ ).

The dielectric constants of toluene/1-hexanol mixtures (100, 80, 75, 70, 65% v/v) were measured using a liquid test fixture (Agilent Technologies model 16452 A, Hyogo, Japan) coupled to an impedance measurement system (Hewlett Packard model 4284 A, Melrose, MA). The capacitance of each liquid and of air was measured, and the dielectric constant was calculated as the ratio of the liquid capacitance to that of air. The measured dielectric constants of pure toluene ( $k_d = 2.4$ ) and decane ( $k_d = 1.85$ ) were consistent with the literature values (2.4 and 1.9, respectively).<sup>47</sup>

Conductivities were measured using a conductivity meter (YSI Inc., Yellow Springs, OH) and a dip cell with cell constant of 0.1  $\text{cm}^{-1}$ . For each measurement, the cell was immersed in the test solution, the temperature allowed to stabilize, and the conductivity recorded.

Surface tensions were measured using a tensiometer (Cole Parmer model EW-59951-14, Vernon Hills, IL) equipped with a De Nouy ring. Average molecular dipole moments of solvent mixtures were calculated according to the method described by Valisko *et al.*<sup>48</sup>

## Results and discussion

We demonstrate that a wide range of liquids can be manipulated in air by digital microfluidics, including organic

solvents and mixtures, aqueous buffers and surfactant solutions, and ionic liquids. These liquids can be categorized based on the conditions under which actuation can be achieved. It will be shown that the results can be explained in terms of the bulk electrical properties of the liquids.

### Organic solvents and mixtures

Table 1 shows the voltage-induced contact angle changes and movabilities of the organic solvents and solutions we evaluated, with water included for comparison. It is immediately apparent that a wide range of liquids can be actuated, and that movement is not predicated on either a high liquid surface tension or on an electrically induced change in the liquid–solid contact angle. These results are illustrated in Fig. 2. Fig. 2a shows the movement of ethanol, which has a low surface tension (22  $\text{dynes cm}^{-1}$ ) and a contact angle change of  $\sim 10^{\circ}$ , while Fig. 2b shows the movement of chloroform, with a surface tension of 27  $\text{dynes cm}^{-1}$  and no voltage-induced contact angle change. As shown in the chloroform movie†, droplet evaporation did not prevent movement as long as droplet size was larger than an electrode. Rapid evaporation of volatile liquids might be a concern if the device were to be operated in air. This problem could be mitigated by operating the device in a closed chamber or by using an open solvent reservoir to saturate the headspace. Solution droplets could also be periodically replenished by merging them with additional droplets of solvent dispensed from a reservoir. A very different strategy for minimizing evaporation is to use filler fluids as the surrounding medium; however, this may lead to expulsion of smaller droplets due to the instability of the liquid contour, as observed by Vallet *et al.*<sup>20</sup> This instability phenomenon may cause undesirable reaction artifacts. Turning now to Fig. 3, we show that droplets of organic liquids such as ethanol can be split (Fig. 3a) and generated from a reservoir (Fig. 3b), demonstrating basic functions that would be needed for performing chemistry on the device.

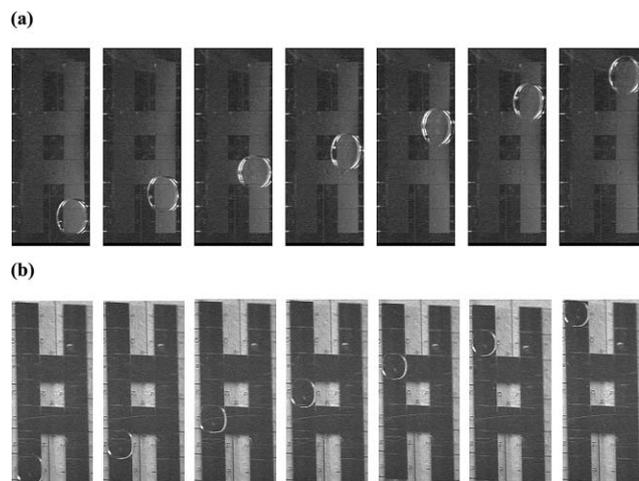
We initially manipulated droplets with 8 kHz AC potentials on devices configured with a 300  $\mu\text{m}$  spacing ( $d$ ) between the top and bottom plates. Liquids that could be moved under these conditions are labeled Y in Table 1. We realized, however, that by reducing  $d$ , and/or by reducing the AC frequency, additional liquids could be moved. These liquids are labeled  $Y^{\diamond}$  in Table 1. (By contrast, liquids labeled Y could be moved in devices in any configuration and any frequency tested.) Liquids that could not be moved under any conditions evaluated are labeled N. In all of these experiments, experimental parameters other than  $d$  and the AC frequency (the magnitude of the applied potential, electrode geometry, dielectric layer material and thickness, *etc.*) were kept constant.

Table 1 lists various physical parameters of the liquids tested, including dipole moment ( $\mu$ ), dielectric constant ( $k_d$ ), conductivity ( $\sigma$ ), and surface tension ( $\gamma$ ), as well as the observed electrically driven contact angle change ( $\Delta\theta$ ). The feasibility of droplet actuation is loosely correlated with  $\mu$  and  $k_d$  (which are interrelated), as well as with  $\sigma$ . In general, liquids with molecular dipole moments greater than 0.9 D, dielectric constants greater than 3 and/or conductivities greater than  $10^{-9}$   $\text{S m}^{-1}$  were movable. Interestingly, unmovable liquids

**Table 1** Organic solvent and solution droplet movement feasibility

Liquid	$\mu/D^a$	$k_d^a$	$\sigma/S \text{ m}^{-1a}$	$\gamma/\text{dynes cm}^{-1a}$	$\Delta\theta/^\circ^a$	Movable <sup>b</sup>
Formamide	3.7	111	$3.5 \times 10^{-3}$ <sup>52</sup>	57	$16.1 \pm 0.4^*$	Y
Water	1.9	80.1	$8.7 \times 10^{-4}$ <sup>*</sup>	72	$30.0 \pm 0^*$	Y
Formic acid	1.4	51.1	$7 \times 10^{-3}$ <sup>53</sup>	37	$26.3 \pm 2^*$	Y
DMSO	4	47.2	$3 \times 10^{-5}$ <sup>52</sup>	43	$15.3 \pm 0.3^*$	Y
DMF	3.8	38.3	$3.2 \times 10^{-5}$ <sup>52</sup>	37	$6.9 \pm 2^*$	Y
Acetonitrile	3.9	36.6	$1.9 \times 10^{-5}$ <sup>52</sup>	29	$9.8 \pm 0.6^*$	Y
Methanol	1.7	33	$1.7 \times 10^{-4}$ <sup>*</sup>	22	$9.8 \pm 1^*$	Y
Ethanol	1.7	25.3	$7.4 \times 10^{-5}$ <sup>*</sup>	22	$10.5 \pm 0.7^*$	Y
Acetone	2.9	21	$5 \times 10^{-7}$ <sup>54</sup>	23	$6.4 \pm 0.2^*$	Y
Piperidine	1.2	4.3	$1 \times 10^{-5}$ <sup>55</sup>	29	$8.9 \pm 0.6^*$	Y
1-Pentanol	1.7	15.1	$8 \times 10^{-7}$ <sup>56</sup>	25	$12.8 \pm 0.8^*$	Y $\diamond$
1-Hexanol	1.8	13	$1.6 \times 10^{-5}$ <sup>*</sup>	26	$14.6 \pm 0.7^*$	Y $\diamond$
Dichloromethane	1.6	8.9	$1 \times 10^{-7}$ <sup>57</sup>	27	$3.7 \pm 0.6^*$	Y $\diamond$
Dibromomethane	1.4	7.8	$2.6 \times 10^{-6}$ <sup>*</sup>	39	$7.3 \pm 1^*$	Y $\diamond$
THF	1.6	7.5	$5 \times 10^{-8}$ <sup>*</sup>	26 <sup>58</sup>	$4.9 \pm 0.9^*$	Y $\diamond$
<i>m</i> -Dichlorobenzene	1.7	5		35	$0.1 \pm 0.1^*$	Y $\diamond$
Chloroform	1	4.8	$7 \times 10^{-8}$ <sup>57</sup>	27	$0.5 \pm 0.4^*$	Y $\diamond$
65% Toluene, 35% 1-hexanol	1.1§	3.7 <sup>*</sup>	$3 \times 10^{-8}$ <sup>*</sup>	28 <sup>*</sup>	$6.1 \pm 3^*$	Y $\diamond$
70% Toluene, 30% 1-hexanol	1§	3.4 <sup>*</sup>		28 <sup>*</sup>	$0.3 \pm 0.3^*$	Y $\diamond$
4-Methyl-3-heptanol	1.23	3.3		25 <sup>59</sup>	$0.1 \pm 0.3^*$	Y $\diamond$
75% Toluene, 25% 1-hexanol	0.9§	3.1 <sup>*</sup>		28 <sup>*</sup>	$0.0 \pm 0.2^*$	Y $\diamond$
4.7 mM TBATFB in toluene		2.3 <sup>*</sup>	$1.8 \times 10^{-7}$ <sup>*</sup>	28 <sup>*</sup>	$5.6 \pm 0.6^*$	Y $\diamond$
80% Toluene, 20% 1-hexanol	0.8§	2.9 <sup>*</sup>		28 <sup>*</sup>	$0.1 \pm 0.3^*$	N
4-Methyl-4-heptanol		2.9		25 <sup>60</sup>	$0.2 \pm 0.2^*$	N
Toluene	0.4	2.4 <sup>*</sup>	$8 \times 10^{-14}$ <sup>58</sup>	28	$0.2 \pm 0.4^*$	N
Carbon tetrachloride	0	2.2	$4 \times 10^{-16}$ <sup>58</sup>	26	$1.0 \pm 0.0^*$	N
Cyclohexane	0	2	$7 \times 10^{-16}$ <sup>58</sup>	25	$0.2 \pm 0.5^*$	N
Decane	0	1.8 <sup>*</sup>		23	$0.5 \pm 0.6^*$	N
<i>p</i> -Dichlorobenzene dissolved in toluene		1.5 <sup>*</sup>				N

<sup>a</sup> Data were measured\* or calculated§ as described in the experimental section; unmarked data are from ref. 47. <sup>b</sup> Liquids marked Y moved under any condition tested (90 V<sub>rms</sub>, 10 Hz–8 kHz, 50 ≤ *d* ≤ 300 μm); liquids marked Y $\diamond$  moved only with a reduced *d* or reduced AC frequency; liquids marked N did not move under any conditions tested.



**Fig. 2** Video sequence (left-to-right): depicting (a) movement of a 0.5 μL droplet of ethanol on a device in which *d* = 300 μm; and (b) movement of a 0.3 μL droplet of chloroform on a device in which *d* = 50 μm. The videos from which these frames were extracted can be seen in the ESI.†

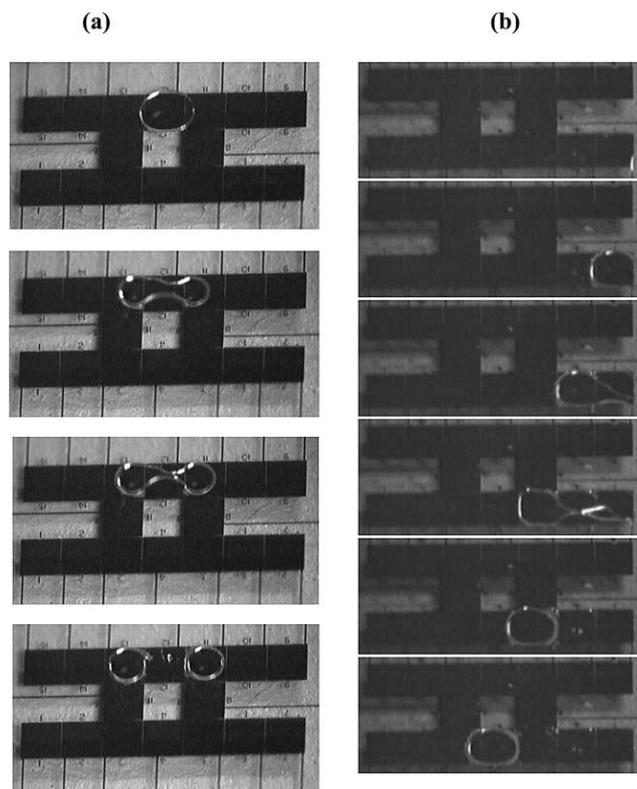
can be made to move as a mixture, as long as the mixture has  $\mu$ ,  $k_d$ , and/or  $\sigma$  above the threshold(s) (e.g., toluene–1-hexanol). Similarly, an unmovable liquid with low conductivity and  $\Delta\theta \approx 0$  can be made to move and exhibit a detectable  $\Delta\theta$  by dissolving an organic salt in it (e.g., TBATFB in toluene).

This is the first report of using digital microfluidics to manipulate droplets of pure and mixed organic solvents in air. These results open the possibility of using digital microfluidics for array-based synthesis, separations that invoke liquid–liquid extraction and biochemical assays that make use of reagents with limited solubility in water.

#### Aqueous surfactants, salt and buffer solutions, and ionic liquids

A wide variety of liquids other than organic solvents can also be moved in air using digital microfluidics (Table 2). These include aqueous surfactants, salt and buffer solutions, and ionic liquids. Each of these liquids exhibited large electrically driven contact angle changes. All liquids in Table 2 moved easily at all frequencies and inter-plate spacings tested.

Aqueous surfactant solutions have low surface tensions and thus low static contact angles. Because organic solvents with these properties exhibit small electrically driven contact angle changes (see Table 1), we expected the surfactant solutions to behave similarly. However, solutions of both charged (e.g., SDS) and neutral (e.g., Triton X-100) surfactants exhibited large  $\Delta\theta$  values (Table 2), and droplet movement was smooth and facile under all conditions tested. Contact angle changes were larger for surfactant solutions above the critical micelle concentrations (cmc); we are exploring this concentration effect further. Regardless, these results indicate that digital microfluidics may be useful for biochemistry-related applications requiring surfactants, such as cell lysis and dissolution of proteins. Surfactant solution droplets might also be useful for



**Fig. 3** Video sequence (top-to-bottom): depicting (a) splitting of a 0.33  $\mu\text{L}$  droplet of ethanol ( $d = 100 \mu\text{m}$ ); and (b) creating a droplet of ethanol ( $d = 50 \mu\text{m}$ ). The videos from which these frames were extracted can be seen in the ESI.†

**Table 2** Movable aqueous surfactants, aqueous salt and buffer solutions, and ionic liquids

Liquid	$\Delta\theta/^\circ$
1% SDS (>cmc)	$30.6 \pm 3$
0.1% SDS (<cmc)	$25.7 \pm 2$
0.5% Triton X-100 (>cmc)	$29.1 \pm 3$
0.005% Triton X-100 (<cmc)	$21.0 \pm 3$
1 mM HEPES	$25.0 \pm 5$
1 mM CHES	$23.3 \pm 2$
100 mM potassium chloride	$22.0 \pm 2$
100 mM sodium phosphate	$22.2 \pm 2$
100 mM sodium borate	$22.3 \pm 2$
[bmim]BF <sub>4</sub>	$28.0 \pm 4$
[bmim]PF <sub>6</sub>	$26.3 \pm 1$

cleaning device surfaces and for solubilizing and transporting dried reagents from on-chip depots.

We observed that, in addition to surfactants, a wide variety of organic and inorganic buffers and salts that are useful for biochemical assays, including HEPES, CHES, KCl, sodium phosphate, and sodium borate, are movable. It should also be noted that high concentrations of proteins ( $\sim 20 \mu\text{M}$ ) can be moved using acetonitrile as a solvent in lieu of previously reported lower concentrations of proteins ( $\sim 2 \mu\text{M}$ ) in DI water.<sup>6</sup> The list of movable surfactants, buffers, and salts in Table 2 is by no means comprehensive; rather, it demonstrates the range of aqueous solutions that are compatible with digital microfluidics.

Ionic liquids, which are salts that are molten at room temperature, have recently become popular for “green chemistry” applications, serving as non-toxic replacements for organic solvents. Here, we report that two commonly used ionic liquids, [bmim]PF<sub>6</sub> and [bmim]BF<sub>4</sub>, can be moved in digital microfluidics devices. These results, along with the capacity to move organic solvents, indicate that integrated digital-microfluidics-based synthesis should be possible.

### Substrate effects

The results reported here are seemingly at odds with our previous report that digital microfluidics could not be used to move acetonitrile–water mixtures containing a large fraction of the organic component.<sup>6</sup> The devices used in this work incorporated thick dielectric layers of parylene (0.98  $\mu\text{m}$ ) or silicon dioxide (1.4  $\mu\text{m}$ ), while devices used previously were formed with much thinner oxide layers ( $\sim 0.1\text{--}0.2 \mu\text{m}$ ).<sup>2–4,6,7</sup> We attribute the differences between our current and previous results to this change in the device design.

### Predicting droplet movement feasibility

Previous work has shown the movement of organic solvents and aqueous surfactants,<sup>28,36,37,61</sup> buffers and protein solutions<sup>18,39,40</sup> in oil. However, this is the first report of moving such liquids in air on a digital microfluidic platform. A prevailing view had been that droplet actuation could be explained by the Young–Lippmann equation, which models the system as a Helmholtz capacitor and assumes the liquid to be a perfect conductor.<sup>2–4,11–14,24–26</sup> According to this model, actuation is a consequence of generating significant voltage induced changes in the surface tension(s) of the droplet: insulating liquids and/or liquids with small electrically driven changes in contact angle would not be expected to be movable. In contrast, the dielectrophoretic mechanism applies to imperfectly conducting liquids with large dielectric constants relative to the surrounding medium.<sup>17–19</sup> The DEP mechanism predicts that organic solvents of the kind reported here would be movable, and recently 1-bromodecane, DMF<sup>28</sup> and DMSO<sup>36</sup> have been successfully moved in silicone oil. Until the present work, however, these liquids had not been actuated in air.

As shown here, droplet actuation is not contingent on generating detectable changes in contact angle. Furthermore, liquids having conductivities ranging from  $\sim 10^{-8}$  to  $10^0 \text{ S m}^{-1}$  can be actuated in the same device. Thus, categorizing liquids as perfect or imperfect conductors is not a particularly useful distinction, either for mechanistic understanding or as a criterion for device design.

It would be useful to be able to predict which liquids can be moved in digital microfluidic devices, and with what design parameters and operating conditions. As noted above, the feasibility of droplet movement is qualitatively correlated with  $\mu$ ,  $k_d$ , and  $\sigma$ , yet these properties alone do not explain why movability depends on the AC frequency used for actuation. A physical parameter that does include the required frequency dependence is the complex permittivity,  $\varepsilon^*$ . It is defined as:

$$\varepsilon^* = \varepsilon_0 \left( k_d - j \frac{\sigma}{\omega \varepsilon_0} \right) \quad (2)$$

where  $\epsilon_0$  is the permittivity of vacuum,  $\sigma$  is conductivity, and  $\omega$  is angular frequency. A liquid with moderate or high conductivity ( $\sigma \geq 10^{-9} \text{ S m}^{-1}$ ) acts as an insulator at high frequency ( $\epsilon^* \approx k_d \epsilon_0$ ), but as a conductor at low frequency ( $\epsilon^* \gg k_d \epsilon_0$ ). A liquid with very low conductivity ( $\sigma \leq 10^{-9} \text{ S m}^{-1}$ ) behaves as a dielectric (insulator) at all frequencies ( $\epsilon^* \approx k_d \epsilon_0$ ).

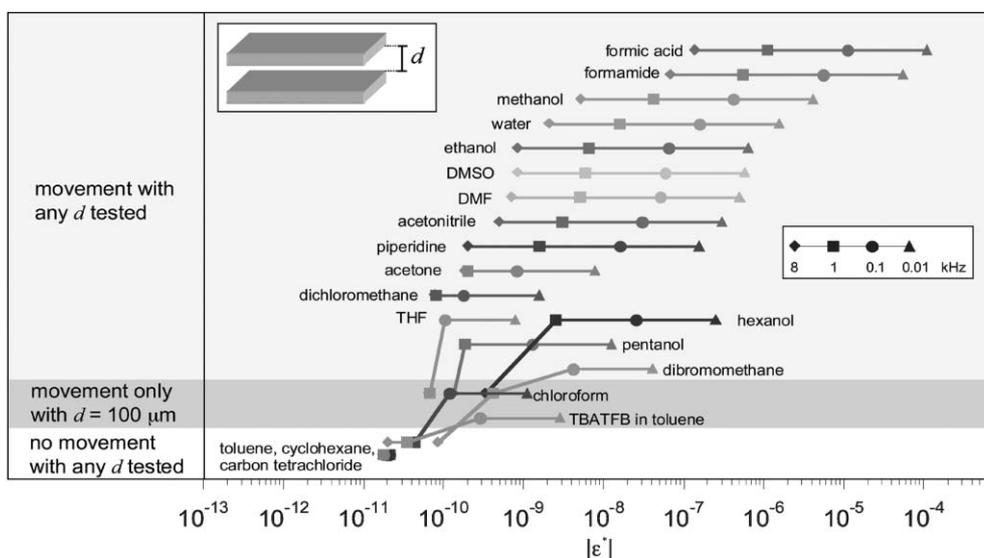
Fig. 4 arranges a subset of liquids from Table 1 (those for which conductivity values were available or were measured) according to their frequency-dependent movability. The  $x$ -axis is the modulus of the complex permittivity,  $|\epsilon^*|$ . We have divided the data into three groups. In the top group, movement was facile in all of the devices tested ( $d$  up to  $300 \mu\text{m}$ ). To move liquids in the middle group, it was necessary to reduce the inter-plate spacing to  $d \leq 100 \mu\text{m}$ . In the bottom group, movement was not observed in any of the devices tested ( $d$  as small as  $50 \mu\text{m}$ ). Looking at Fig. 4 from right to left, we see that when  $|\epsilon^*|$  was greater than  $2 \times 10^{-9}$ , liquids were movable regardless of the inter-plate spacing. When  $|\epsilon^*|$  was greater than  $8 \times 10^{-11}$  but less than  $2 \times 10^{-9}$ , the liquids were movable, but some required a smaller inter-plate spacing. When  $|\epsilon^*|$  was less than  $8 \times 10^{-11}$ , the liquids could not be moved with any spacing. Thus,  $|\epsilon^*|$  can be used to predict liquid movability.

From Fig. 4 it is clear that the movability of some liquids depends on the gap dimension. We considered the possibility that evaporation could explain this trend. For droplets of equal size, one in a  $300 \mu\text{m}$  gap would be expected to evaporate more quickly than one in a  $50 \mu\text{m}$  gap, because a larger fraction of its surface area would be exposed to air. This leads to the prediction that more volatile liquids should be more difficult to move with larger gaps. In fact, we found that dichloromethane, a very volatile liquid, (b.p.  $40^\circ\text{C}$ ) could be moved at all gaps tested, while *m*-DCB, a nonvolatile liquid (b.p.  $172^\circ\text{C}$ ) could only be moved with the smallest gap tested,

$50 \mu\text{m}$ . We propose instead that the observed gap dependence can be explained in terms of the forces acting on the droplets. For a given applied voltage, a narrower gap will result in a higher field in the dielectric liquid, and hence in a larger force acting on the droplet. Droplets that cannot be moved with large gaps may therefore be movable with smaller ones. Experiments are under way to determine whether low polarity liquids such as toluene, which could not be moved even with  $50 \mu\text{m}$  gaps, can be moved in devices with reduced gaps.

The speed of droplet movement will depend on the applied electric field, the size of the electrode, and the opposing drag forces. Results of experiments on electrowetting-driven motion of aqueous droplets in oil suggest that the liquid–liquid surface tension also affects the movement speed, so in our system the liquid–vapor surface tension may play a role.<sup>49</sup> Because in the experiments shown here the electrodes were activated manually, it was not possible to characterize the effects of these parameters on droplet speed. In a device in which electrode activation is automated, the rate of droplet movement should be an observable parameter, and we intend to examine this in the future.

The dependence of droplet movement on the applied frequency is similar to what Gascoyne *et al.*,<sup>28</sup> Jones and coworkers<sup>29–31</sup> and Zeng and Korsmeyer<sup>32</sup> have proposed. This, however, is the first report of using a readily available physical parameter to predict the feasibility of droplet movement. We are currently developing a comprehensive model to evaluate the relative contributions of electrostatic and dielectrophoretic forces to droplet actuation. In this effort, we will use finite element modeling to analyze the forces generated in droplets as well as drag forces that oppose movement that vary with surface tension and viscosity. In the meantime,  $\epsilon^*$  is useful for predicting which liquids can be actuated, and at what frequencies.



**Fig. 4** Plot of droplet movement feasibility as a function of the modulus of the complex permittivity,  $\epsilon^*$ . Liquids in the top group could be moved at the indicated frequencies (symbols) in devices with all spacings tested ( $d$  up to  $300 \mu\text{m}$ ). Liquid/frequency combinations in the middle group could be moved only in devices with reduced spacing ( $50 \leq d \leq 100 \mu\text{m}$ ). Liquid/frequency combinations in the bottom group could not be moved with any spacing tested ( $50 \leq d \leq 300 \mu\text{m}$ ). Within each group, the liquids are arranged arbitrarily.

## Conclusion

We have reported that organic solvents, aqueous surfactants, and ionic liquids can be manipulated in air in digital microfluidic devices. The range of liquids that can be moved by applying an electrical potential is much wider than has been reported previously. Liquids such as chloroform, DMF, and acetone, 1% SDS, and [bmim]BF<sub>4</sub>, can be moved by applying identical voltages and frequencies to a single device. Our results suggest that the frequency-dependent complex permittivity,  $\epsilon^*$ , can be used to predict whether droplets of a particular liquid are likely to be movable.

The feasibility of actuating droplets of a wide range of liquids enables many processes and applications that were previously assumed to be incompatible with digital microfluidics. By actuating organic liquids and surfactant solutions in air rather than in oil, one eliminates the potential problems of emulsification and liquid–liquid phase transfer. Droplets of solvents or surfactant solutions could be used to clean the device surface by dissolving and removing contaminants or debris. Of potential concern is the tendency of liquids such as methanol and chloroform to partition into Teflon-AF (e.g., the equilibrium concentration of chloroform in Teflon-AF is 8 g per 100 g polymer).<sup>50</sup> While these solvents do plasticize Teflon-AF, this actually *reduces* the tendency for small solutes to diffuse into the material.<sup>50,51</sup> This phenomenon could be exploited by transporting organic solvents such as chloroform across the Teflon-AF surface prior to actuating analyte droplets, enabling the analytes to be transported more efficiently across the device. More general applications of the results reported here include array-based synthesis, separations that utilize liquid–liquid extractions, biochemical assays that make use of reagents with limited solubility in water, and on-chip cell lysis.

## Acknowledgements

We thank Jim Sterling and Chris Cooney from the Keck Graduate Institute and Ben Shapiro from the University of Maryland for helpful discussions. The assistance of Halil Berberoglu and Ilup Jin (UCLA) in measuring surface tensions and dielectric constants is gratefully acknowledged. The Center for Cell Mimetic Space Exploration (CMISE), a NASA University Research, Engineering and Technology Institute (URETI), under award number NCC 2-1364, supported this work. ARW thanks the NIH for an NRSA postdoctoral fellowship.

## References

- 1 D. R. Reyes, D. Iossifidis, P. A. Auroux and A. Manz, Micro Total Analysis Systems. 1. Introduction, Theory, and Technology, *Anal. Chem.*, 2002, **74**, 2623–2636.
- 2 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**, 259–268.
- 3 H. Moon, S. K. Cho, R. L. Garrell and C.-J. Kim, Low Voltage Electrowetting-on-Dielectric, *J. Appl. Phys.*, 2002, **92**, 4080–4087.
- 4 S. K. Cho, H. Moon and C.-J. Kim, Creating, Transporting, Cutting, and Merging Liquid Droplets by Electrowetting-Based Actuation for Digital Microfluidic Circuits, *J. Microelectromech. Syst.*, 2003, **12**, 70–80.
- 5 K. Seiler, D. J. Harrison and A. Manz, Planar Glass Chips for Capillary Electrophoresis: Repetitive Sample Injection, Quantitation, and Separation Efficiency, *Anal. Chem.*, 1993, **65**, 1481–1488.
- 6 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 (MALDI-MS), *Anal. Chem.*, 2004, **76**, 4833–4838.
- 7 A. R. Wheeler, H. Moon, C. A. Bird, R. R. O. Loo, C.-J. Kim, J. A. Loo and R. L. Garrell, Digital Microfluidics with In-Line Sample Purification for Proteomics Analyses with MALDI-MS, *Anal. Chem.*, 2005, **77**, 534–540.
- 8 M. A. Burns, B. N. Johnson, S. N. Brahmasandra, K. Handique, J. R. Webster, M. Krishnan, T. S. Sammarco, P. N. Man, D. Jones, D. Heldsinger, C. H. Mastrangelo and D. T. Burke, An Integrated Nanoliter DNA Analysis Device, *Science*, 1998, **282**, 484–487.
- 9 K. Handique, D. T. Burke, C. H. Mastrangelo and M. A. Burns, Nanoliter Liquid Metering in Microchannels Using Hydrophobic Patterns, *Anal. Chem.*, 2000, **72**, 4100–4109.
- 10 M. Yamada and M. Seki, Nanoliter-Sized Liquid Dispenser Array for Multiple Biochemical Analysis in Microfluidic Devices, *Anal. Chem.*, 2004, **76**, 895–899.
- 11 M. G. Pollack, R. B. Fair and A. D. Shenderov, Electrowetting-Based Actuation of Liquid Droplets for Microfluidic Applications, *Appl. Phys. Lett.*, 2000, **77**, 1725–1726.
- 12 M. G. Pollack, A. D. Shenderov and R. B. Fair, Electrowetting-Based Actuation of Droplets for Integrated Microfluidics, *Lab Chip*, 2002, **2**, 96–101.
- 13 P. Paik, V. K. Pamula and R. B. Fair, Rapid Droplet Mixing for Digital Microfluidics, *Lab Chip*, 2003, **3**, 253–259.
- 14 P. Paik, V. K. Pamula, M. G. Pollack and R. B. Fair, Electrowetting-Based Droplet Mixers for Microfluidic Systems, *Lab Chip*, 2003, **3**, 28–33.
- 15 M. Washizu, Electrostatic Actuation of Liquid Droplets for Microreactor Applications, *IEEE Trans. Ind. Appl.*, 1998, **34**, 732–737.
- 16 T. Taniguchi, T. Torii and T. Higuchi, Chemical Reactions in Microdroplets by Electrostatic Manipulation of Droplets in Liquid Media, *Lab Chip*, 2002, **2**, 19–23.
- 17 O. D. Velev, B. G. Prevo and K. H. Bhatt, On-Chip Manipulation of Free Droplets, *Nature*, 2003, **426**, 515–516.
- 18 J. A. Schwartz, J. V. Vykoukal and P. R. C. Gascoyne, Droplet-Based Chemistry on a Programmable Micro-Chip, *Lab Chip*, 2004, **4**, 11–17.
- 19 J. R. Millman, K. H. Bhatt, B. G. Prevo and O. D. Velev, Anisotropic Particle Synthesis in Dielectrophoretically Controlled Microdroplet Reactors, *Nat. Mater.*, 2005, **4**, 98–102.
- 20 M. Vallet, B. Berge and L. Vovelle, Electrowetting of Water and Aqueous Solutions on Poly(Ethylene Terephthalate) Insulating Films, *Polymer*, 1996, **37**, 2465–2470.
- 21 M. Vallet, M. Vallade and B. Berge, Limiting Phenomena for the Spreading of Water on Polymer Films by Electrowetting, *Eur. Phys. J. B*, 1999, **11**, 583–591.
- 22 H. J. Verheijen and M. W. J. Prins, Reversible Electrowetting and Trapping of Charge: Model and Experiments, *Langmuir*, 1999, **15**, 6616–6620.
- 23 C. Quilliet and B. Berge, Electrowetting: A Recent Outbreak, *Curr. Opin. Colloid Interface Sci.*, 2001, **6**, 34–39.
- 24 V. Peykov, A. Quinn and J. Ralston, Electrowetting: A Model for Contact-Angle Saturation, *Colloid Polym. Sci.*, 2000, **278**, 789–793.
- 25 R. Digilov, Charge-Induced Modification of Contact Angle: The Secondary Electrocapillary Effect, *Langmuir*, 2000, **16**, 6719–6723.
- 26 K. H. Kang, How Electrostatic Fields Change Contact Angle in Electrowetting, *Langmuir*, 2002, **18**, 10318–10322.
- 27 B. Shapiro, H. Moon, R. L. Garrell and C.-J. Kim, Equilibrium Behavior of Sessile Drops under Surface Tension, Applied External Fields, and Material Variations, *J. Appl. Phys.*, 2003, **93**, 5794–5811.
- 28 P. R. C. Gascoyne, J. V. Vykoukal, J. A. Schwartz, T. J. Anderson, D. M. Vykoukal, K. W. Current, C. McConaghy, F. F. Becker and C. Andrews, Dielectrophoresis-Based Programmable Fluidic Processors, *Lab Chip*, 2004, **4**, 299–309.
- 29 T. B. Jones, On the Relationship of Dielectrophoresis and Electrowetting, *Langmuir*, 2002, **18**, 4437–4443.

- 30 T. B. Jones, J. D. Fowler, Y. S. Chang and C.-J. Kim, Frequency-Based Relationship of Electrowetting and Dielectrophoretic Liquid Microactuation, *Langmuir*, 2003, **19**, 7646–7651.
- 31 T. B. Jones, K.-L. Wang and D.-J. Yao, Frequency-Dependent Electromechanics of Aqueous Liquids: Electrowetting and Dielectrophoresis, *Langmuir*, 2004, **20**, 2813–2818.
- 32 J. Zeng and T. Korsmeyer, Principles of Droplet Electrohydrodynamics for Lab-on-a-Chip, *Lab Chip*, 2004, **4**, 265–277.
- 33 O. M. Stuetzer, Ion Drag Pumps, *J. Appl. Phys.*, 1960, **31**, 136–146.
- 34 J. R. Melcher, Travelling Wave Induced Electroconvection, *Phys. Fluids*, 1966, **9**, 1548–1555.
- 35 S. F. Bart, L. S. Tavrow, M. Mehregany and J. H. Lang, Microfabricated Electrohydrodynamic Pumps, *Sens. Actuators, A*, 1990, **21**, 193–197.
- 36 V. K. Pamula, V. Srinivasan, H. Chakrapani, R. B. Fair and E. J. Toone, A Droplet-Based Lab-on-a-Chip for Colorimetric Detection of Nitroaromatic Explosives, *Proc. IEEE Conf. MEMS*, 2005, 722–725.
- 37 P. Paik, V. K. Pamula and K. Chakrabarty, Thermal Effects on Droplet Transport in Digital Microfluidics with Applications to Chip Cooling, *Itherm 2004, 9th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, 2004, pp. 649–654.
- 38 V. Srinivasan, V. K. Pamula, M. G. Pollack and R. B. Fair, A Digital Microfluidic Biosensor for Multianalyte Detection, *Proc. IEEE Conf. MEMS*, 2003, 327–330.
- 39 V. Srinivasan, V. K. Pamula, P. Paik and R. B. Fair, Protein Stamping for MALDI Mass Spectrometry Using an Electrowetting-Based Microfluidic Platform, *Lab-on-a-Chip: Platforms, Devices, and Applications Proceedings of SPIE Optics East, Philadelphia, Pennsylvania*, 2004, p. 5591.
- 40 V. Srinivasan, V. K. Pamula and R. B. Fair, An Integrated Digital Microfluidic Lab-on-a-Chip for Clinical Diagnostics on Human Physiological Fluids, *Lab Chip*, 2004, **4**, 310–315.
- 41 V. Srinivasan, V. K. Pamula and R. B. Fair, Droplet-Based Microfluidic Lab-on-a-Chip for Glucose Detection, *Anal. Chim. Acta*, 2004, **507**, 145–150.
- 42 E. Seyrat and R. A. Hayes, Amorphous Fluoropolymers as Insulators for Reversible Low-Voltage Electrowetting, *J. Appl. Phys.*, 2001, **90**, 1383–1386.
- 43 F. Saeki, J. Baum, H. Moon, J.-Y. Yoon, C.-J. Kim and R. L. Garrell, Electrowetting on Dielectrics (EWOD): Reducing the Voltage Requirements for Microfluidics, *Polym. Mater. Sci. Eng.*, 2001, **85**, 12–13.
- 44 J.-Y. Yoon and R. L. Garrell, Preventing Biomolecular Adsorption in Electrowetting-Based Microchips, *Anal. Chem.*, 2003, **75**, 5097–5102.
- 45 C. D. Meinhart, M. Sigurdson and D. Tretheway, Analysis of Microscale Transport for Biomems, *Proceedings of the First International Symposium on Micro & Nano Technology, Honolulu, Hawaii*, 2004.
- 46 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.
- 47 D. R. Lide, *CRC Handbook of Chemistry and Physics*, CRC Press, New York, NY, 84th edn, 2003.
- 48 M. Valisko, D. Boda, J. Liszi and I. Szalai, Relative Permittivity of Dipolar Liquids and Their Mixtures. Comparison of Theory and Experiment, *Phys. Chem. Chem. Phys.*, 2001, **3**, 2995–3000.
- 49 T. Roques-Carnes, S. Palmier, R. A. Hayes and L. J. M. Schlangen, The Effect of the Oil/Water Interfacial Tension on Electrowetting Driven Fluid Motion, *Colloids Surf., A*, 2005, **267**, 56–63.
- 50 H. Zhao, J. Zhang, N. Wu, X. Zhang, K. Crowley and S. G. Weber, Transport of Organic Solutes through Amorphous Teflon AF Films, *J. Am. Chem. Soc.*, 2005, **127**, 15112–15119.
- 51 H. Zhao, K. Ismail and S. G. Weber, How Fluorous Is Poly(2,2-bis(trifluoromethyl)-4,5-difluoro-1,3-dioxide-co-tetrafluoroethylene) (Teflon AF)?, *J. Am. Chem. Soc.*, 2004, **126**, 13184–13185.
- 52 D. A. Owensby, A. J. Parker and J. W. Diggle, Solvation of Ions. XXI. Solvation of Potassium Cation in Nonaqueous Solvents, *J. Am. Chem. Soc.*, 1974, **96**, 2682–2688.
- 53 M. Arnac and G. Verboom, Voltammetric and Chronopotentiometric Studies of the Quinone and Hydroquinone System in Anhydrous Formic Acid, *Anal. Chem.*, 1977, **49**, 806–809.
- 54 D. S. Gill, A. N. Sharma and H. Schneider, Acetone + N,N-Dimethylformamide Solvent System. Part 2.—Conductance Studies of Some Electrolytes in Acetone + N,N-Dimethylformamide Mixtures at 25 °C, *J. Chem. Soc., Faraday Trans. 1*, 1982, **78**, 465–474.
- 55 J. A. Dean, *Langes Handbook of Chemistry*, McGraw Hill Inc., New York, 14th edn, 1992.
- 56 W. Furmanski, I. Strzalkowski and J. Hurwic, Notes des Membres et Correspondants et Notes Presentees ou Transmises par Leurs Soins, *C. R. Hebd. Seances Acad. Sci., Ser. C*, 1973, **277**, 223–225.
- 57 E. Iwamoto, K. Ito and Y. Yamamoto, Solute–Solvent Interactions in Ion-Pair Extraction of Tetraalkylammonium Iodides. I. A New Approach to the Extraction Constant, *J. Phys. Chem.*, 1981, **85**, 894–901.
- 58 J. A. Riddick and W. B. Bunger, *Organic Solvents*, Wiley-Interscience, New York, NY, 3rd edn, 1970, vol. 2.
- 59 G. L. Dorough, H. B. Glass, T. L. Gresham, G. B. Malone and E. E. Reid, Structure–Property Relationships in Some Isomeric Octanols, *J. Am. Chem. Soc.*, 1941, **63**, 3100–3110.
- 60 K. Owen, O. R. Quayle and E. M. Beaves, A Study of Organic Parachors II. Temperature and III. Constitutive Variations of Parachors of a Series of Tertiary Alcohols, *J. Am. Chem. Soc.*, 1939, **61**, 900–905.
- 61 M. G. Pollack, *Electrowetting-Based Microactuation of Droplets for Digital Microfluidics*, PhD Dissertation, Duke University, Durham, N.C., 2001.