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Citation: Applied Physics Letters **101**, 174102 (2012); doi: 10.1063/1.4764020
View online: http://dx.doi.org/10.1063/1.4764020
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Reconfigurable liquid metal circuits by Laplace pressure shaping

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(Received 13 September 2012; accepted 8 October 2012; published online 24 October 2012)

We report reconfigurable circuits formed by liquid metal shaping with <10 pounds per square inch (psi) Laplace and vacuum pressures. Laplace pressure drives liquid metals into microreplicated trenches, and upon release of vacuum, the liquid metal dewets into droplets that are compacted to 10–100× less area than when in the channel. Experimental validation includes measurements of actuation speeds exceeding 30 cm/s, simple erasable resistive networks, and switchable 4.5 GHz antennas. Such capability may be of value for next generation of simple electronic switches, tunable antennas, adaptive reflectors, and switchable metamaterials. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4764020]

The term "reconfigurable electronics" covers a wide variety of technologies, ranging from field-programmable gate arrays to radio-frequency micro-electro-mechanical systems. These conventional approaches use electronic switches to dynamically alter the interconnections between a static layout of electrical wires. What if instead, we could dynamically reconfigure, erase, or write, the electrical circuit wiring itself? Such capability would be of significant value for simple electronic switches, tunable antennas, adaptive microwave reflectivity, and switchable metamaterials, to name a few applications. For example, reconfiguring antenna circuits can dramatically change the resonant wavelength, as commercially proven with mechanical switches, transistors, or diodes.[1] Recently, there has been growing interest in use of microfluidics to reconfigure simple circuits and antennas including integration into soft/conformal substrates.[2–8] However, many of these prior approaches switch slowly, require bulky external control systems, and cannot reconfigure the actual wires comprising the circuit. We report on an approach for reconfigurable circuits, based on competitive liquid metal shaping with Laplace and vacuum pressures. With <10 pounds per square inch (psi) vacuum applied to two plastic films, one film having a network of microreplicated trenches, Laplace pressure drives liquid metals such as eutectic GaIn or Hg into the trenches. Upon release of vacuum, the liquid metal pattern is erased, as it rapidly dewets into droplets that compact to 10–100× less area than when in the trenches (Fig. 1). This work includes measurements of actuation speeds, formation of simple erasable resistive networks, and demonstration of a switchable 4.5 GHz dipole antenna. Advantages of this approach include: ultra-simple and scalable fabrication; ultra-simple operation with few peripheral controls or interconnects; vacuum actuation, or even as simple as fingertip pressure. Collectively, this work provides both greater simplicity, and in some aspects improved performance for applications such as large flexible sheets of switchable metamaterials, ultra-low-cost tunable antennas, and tunable transmittance or reflectance of large-area electromagnetic shielding.

Devices were fabricated by layering at least two polyethylene terephthalate (PET) or polyimide films with a liquid metal droplet in between each (Fig. 1). One film includes several trench features on the order of 10's to 100's of μm deep and wide, typically with a <1:1 aspect ratio (height:-width). The channels can be formed by hot-embossing of the PET or by applying an additional patterned film by photolithography or laser machining. A variety of such conventional techniques was used in this work and had no significant

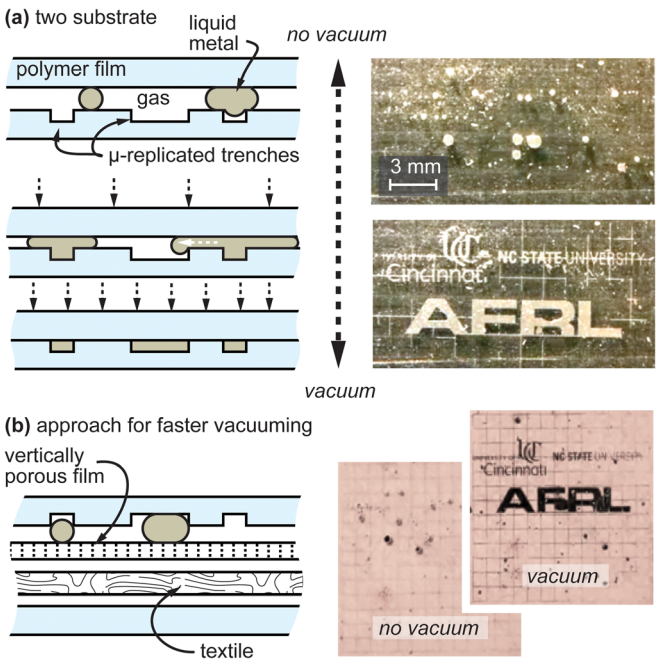


FIG. 1. Basic device diagrams and operation (left) and photographs of demonstrations (right) of several liquid metal logos interconnected with a liquid metal mesh pattern.

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influence on the achieved results. In simple experiments (Fig. 1(a)), the two films were placed on a 10 psi vacuum table, with the upper substrate larger in area and covering all vacuum holes in the vacuum table. This works well, but the rate of gas evacuation slows as the two films come closer together (increasing the resistance to gas flow).

For larger area and faster demonstrations, an improved approach (Fig. 1(b)) included a 30 μm polyimide membrane track-etched with 0.4 μm diameter vertical pores at a density of 1.5×10^8 cm^{-2} (AR Brown-US). This allows gas to rapidly evacuate vertically, while confining the liquid metal because the required capillary pressure for the liquid metal to enter the pores is >300 psi. Between the track-etched membrane and the vacuum table a textile is placed to promote rapid horizontal evacuation of gas to the edge of the films. Instead of the vacuum table, one could use a simple connection to a single vacuum line. Suitable vacuum pressures can be achieved with standard vacuum pumps, but miniaturized options include venturi, piston, and diaphragm pumps (e.g., Dynaflo 4122X, weight = 12 g). The liquid metals tested are listed in Table I and include Hg, eutectic Ga-In, and Galinstan (68.5% Ga, 21.5% In, and 10% Sn). The latter two liquid metals require inert gas such as N_2 or a slight hydrochloric acid vapor to prevent formation of a rigid surface oxide in the presence of oxygen >1 ppm.[14] The liquid metals have a ~10× lower conductivity than a standard circuit material like Cu. However, use of 50–150 μm deep trenches can provide a greater thickness (t) than typical Cu films and therefore provide suitable sheet resistance ($R_S = 1/\sigma t$, Ω/□). Liquid metals were dosed using manual micropipetting. Regarding high power (temperature) operation, the polyimide films limit the maximum working temperature of the devices to ~250 °C. For antenna demonstrations, solid electrode contacts were provided by photolithography and etching of Cu electrode lines or by inserting wire electrodes through the films and sealing the wires with a UV epoxy.

All devices in this work, manipulate the liquid metal by vacuum collapsing of a planar microfluidic channel. As the channel collapses the Laplace pressure increases for the liquid in that channel,[25] forcing the liquid into trenches which provide lower-Laplace pressure (Fig. 1). The Laplace pressure of the liquid in the channel can be calculated according to the Laplace equation:

$$\Delta p_{channel} = \gamma(1/R_V + 1/R_H)\,(Nm^{-2}), \qquad (1)$$

where γ is the interfacial surface tension of the liquid metal and ambient medium, R_V and R_H are the vertical and horizontal radii of curvature for the liquid meniscus in the planar channel. γ is very high for liquid metals, such that the polymers tested herein are not wetted by the liquid metal. As a result, R_V can be approximated as half the planar channel height (h). When the planar channel begins to collapse, R_H can be ignored because R_V becomes much smaller than R_H. The case for calculating Laplace pressure in a trench of dimension x is similar (Fig. 2). Therefore, the resulting Laplace pressure in the planar channel, or a trench, can be calculated as

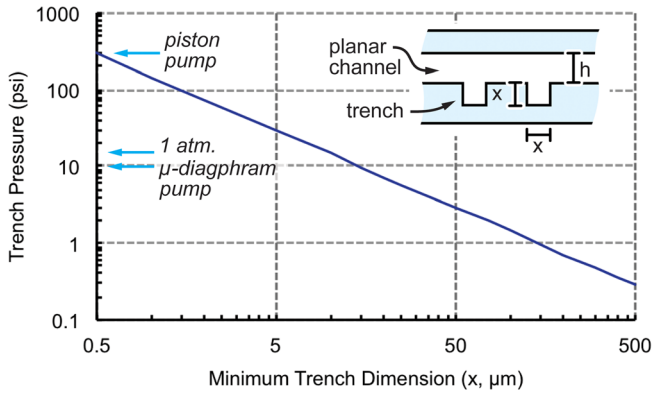


FIG. 2. Required Laplace pressure to move liquid metal of $\gamma = 0.5$ Nm^{-1} into a trench as a function of scaling the trench dimensions (x). One psi is equal to 6894.8 Nm^{-2}.

$$\Delta p_{channel} = 2\gamma/h, \quad \Delta p_{trench} = 2\gamma/x. \qquad (2)$$

The liquid in the channel will wet into a trench as soon as the Laplace pressure imparted by the channel geometry exceeds the Laplace pressure that the trench imparts on the liquid, and dewets the trench when this balance is reversed.

Fig. 2 uses Eq. (2) to plot threshold Laplace pressure required to move the liquid metal into trenches with varying dimension x. The channel pressure is equal to the applied vacuum pressure and therefore cannot exceed atmospheric pressure (1 atm = 14.7 psi at sea-level). Several interesting considerations should be communicated. First, trenches with dimensions similar to conventional Cu wiring on circuit boards (x ~ 50 μm) only require ~2.9 psi of pressure differential for actuation. 2.9 psi pressure can even be achieved at 30 000 ft. of altitude above sea-level, approximately equal to the elevation of Mt. Everest. At sea-level (again, 14.7 psi) vacuum actuation is possible down to trenches as small as 10 μm. These levels of vacuum are easily provided by conventional Food-Saver™ vacuum pumps or tiny μ-diaphragm pumps (labeled in Fig. 2). One might wonder how to actuate much smaller geometries such as wiring used for

TABLE I. Melting point, boiling point, vapor pressure, density, viscosity, surface tension, and conductivity for several liquids. Cu is listed for comparison only.

	T_m (°C)	T_b (°C)	p_v (psi)	ρ (g cm^{-3})	ν (cSt)	γ (Nm^{-1})	σ (10^7 Sm^{-1})
Ga-In	15.7 (Ref. 9)	>10^3 (no data)	<10^{-13} (Ref. 10)	6.3 (Ref. 9)	0.32 (Ref. 11)	0.624 (Ref. 12)	0.34 (Ref. 11)
Ga-In-Sn	−19 (Ref. 13)	>10^3 (Ref. 13)	<10^{-10} (Ref. 14)	6.4 (Ref. 13)	0.37 (Ref. 13)	0.535 (Ref. 14)	0.38 (Ref. 13)
Hg	−39 (Ref. 13)	357 (Ref. 13)	<10^{-4} (Ref. 15)	13.5 (Ref. 13)	0.11 (Ref. 13)	0.428 (Ref. 16)	0.10 (Ref. 13)
Cu	1085 (Ref. 17)	…	…	…	…	…	5.95 (Ref. 18)
NaCl 25 wt. %	−21 (Ref. 19)	106 (Ref. 19)	0.255 (Ref. 20)	1.2 (Ref. 21)	1.63 (Ref. 22)	0.079 (Ref. 23)	22.20 × 10^{-7} (Ref. 24)

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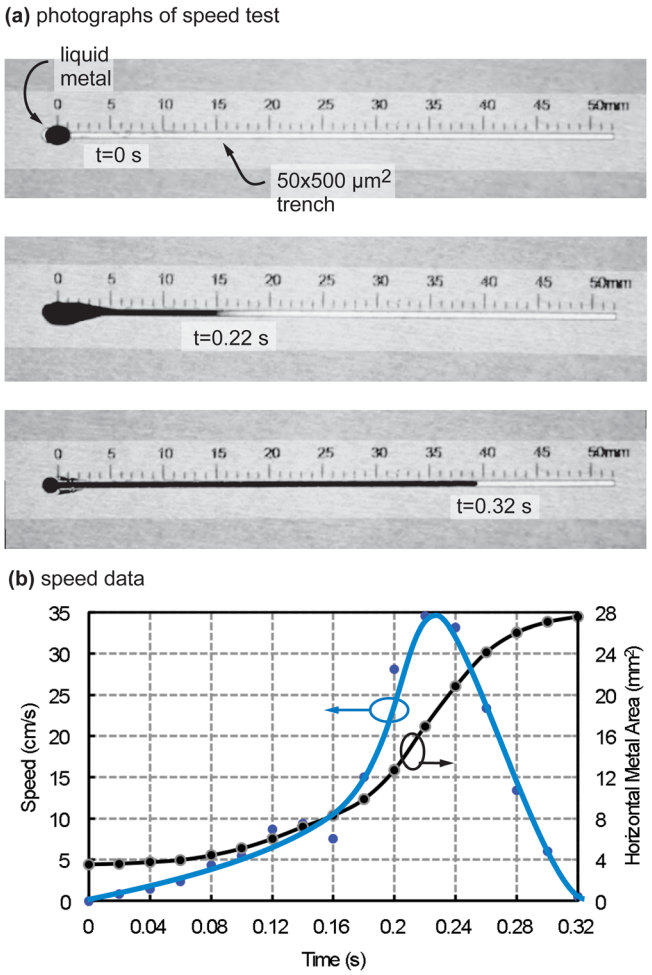


FIG. 3. Liquid actuation speed test for liquid metal driven into a 50 μm deep Kapton channel with ~10 psi pressure, including: (a) time-lapse photographs of the tests; (b) advancing speed and horizontal area of the liquid metal vs. time.

microprocessors or infrared metamaterials ($x \sim 0.1\ \mu m$).[26] This will be addressed later in this article.

The intent of this paper is to demonstrate some of the main functions of the reported vacuum actuation approach. Function and performance were demonstrated by testing speed, circuit patterns, resonators, and antenna switching. The experiments tested herein were actuated using a Welch 2511B-01 vacuum pump applying ~10 psi pressure.

Speed tests were performed with a linear channel. High-speed camera photographs were analyzed using ImageJ software (Fig. 3). The results for a $50 \times 500\ \mu m$ trench reveal actuation speeds up to $\sim 34\ cm\ s^{-1}$ with associated changes in visible area of the liquid metal ranging from 4 mm^2 to 28 mm^2. This result shows that actuation is fast from a microfluidics perspective (typically $<10\ cm\ s^{-1}$),[27] without any optimization and using the architecture shown in Fig. 1(a) as a worst case scenario.

Next, several simple circuit patterns were tested to visually demonstrate how the liquid metal can be actuated in interconnected or isolated formats. Simple resistive networks are demonstrated in Fig. 4. These demonstrations are primarily visible but would be fully functional with electrode connections. To ensure the resistor portions of the circuit are highly resistive, the trench for the resistor portion can simply be made more shallow or narrower. For example, a

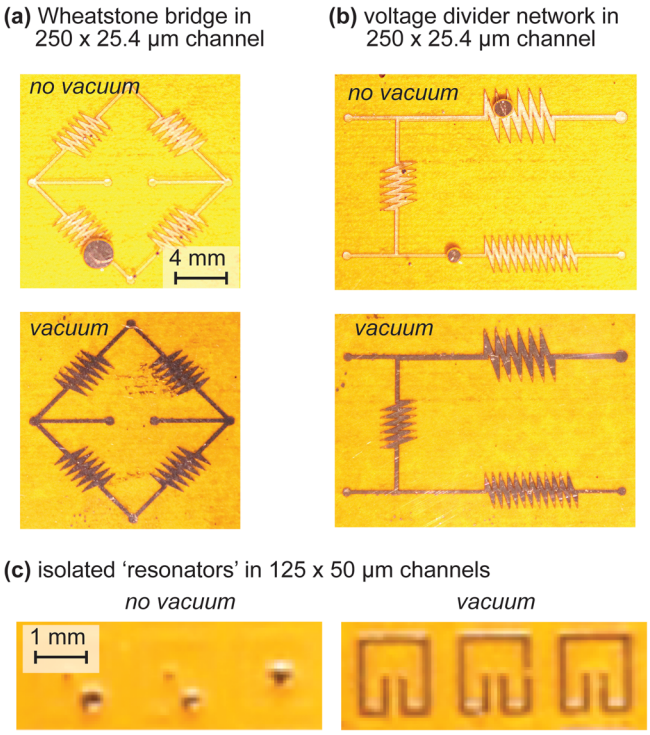


FIG. 4. Switching of (a),(b) resistive networks and (c) isolated "resonators," all using the device structure of Fig. 1(b).

$500 \times 200\ \mu m$ wide/deep trench could be locally reduced to $10 \times 10\ \mu m$, although requiring a higher driving pressure, will result in a $1000\times$ increase in resistance. Liquid metal circuits can also be formed in isolated fashion, as demonstrated in Fig. 4(c). Each individual "split-ring resonator" shape is $1.25\ mm \times 1.375\ mm \times 0.125\ mm$. A larger liquid metal droplet was first dosed, vacuum actuated to split into filling of all three resonator trenches, then with the release of vacuum dewet the trenches to form 3 individual droplets near each trench. A more precise automatic dosing technique is described in the supplementary material.[28]

To demonstrate a functional electronic circuit, a switchable dipole antenna was tested. The antenna had a length ~52 mm and was measured for GHz resonance in both the vacuumed and non-vacuumed states (Fig. 5). The device demonstrated resonance at ~4.5 GHz in the vacuum state. The liquid metal switching was shown to operate equally well in planar form or when flexed (inset photograph of Fig. 5). The experimental resonance data was compared to simulation with Agilent's Advanced Design Systems software. The simulation results plotted in Fig. S1 of supplementary material[28] confirm that in addition to proper vacuum actuation, the antenna functions electrically as an antenna with a fixed geometry (solid metal) would.

Practical application will require modification of the basic test devices presented herein, but the simplicity of operation will remain the same. Some areas of development include: (1) localizing liquid metal droplets in the non-vacuumed state for more rapid and reliable transposition between the channel and trench; (2) extension to alternate electromagnetic liquid systems; (3) scaling to smaller trench dimensions.

Regarding the need for localization of liquid metal droplets, one could potentially incorporate smaller flexible domes

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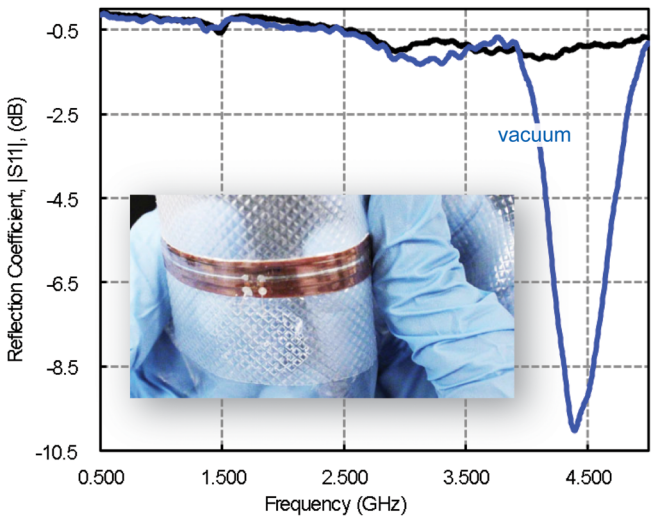


FIG. 5. Reflection data from a switchable liquid metal antenna: with inset photo of the device.

instead of a single large superstrate. Ideally, the device structure of Fig. 1(b) would be utilized, with the porous film and dome each confining a precise volume of liquid metal. This does not necessarily preclude the use of electrical connection of liquid metal between domes, with the main issue being reliable splitting of liquid metal when releasing vacuum.

Regarding alternate electromagnetic liquids, the switching scheme is not limited to the applications and materials reported herein. Alternate fluids could include dielectric fluids, ferrofluids, fluids with visual or infrared coloration, and other liquids or fluids that alter some interaction with external electromagnetic radiation. Liquid metals have a very high surface tension ($\gamma \sim 0.5$ Nm^{-1}), such that their contact angle (Young's angle) easily exceeds 135° on almost any surface, allowing dewetting from the 90° corners of the trenches. Conventional polar liquids ($\gamma \sim 0.05$ Nm^{-1}) would require an oil phase in place of the gas and/or[29] a superhydrophobic surface. Superhydrophobicity can be achieved even for non-polar liquids like oils.[30] Therefore, the physics of operation extends to additional fluid systems, with the key requirement being proper dewetting of the fluid from the trenches.

The next concerns are scaling to smaller trench dimensions and on achieving larger changes in the switchable area of liquid metals. Actuation at greater than atmospheric pressure would require pressure delivery using a different mechanism than that shown in Fig. 1. For example, miniature electronic piston pumps can easily provide the *positive* pressure required for actuation of trenches that are only 100's of nm, but this assumes that pressure is delivered reliably. If pressure was delivered by polymer channels, the channels could be of small enough area to limit the potentially damaging force caused by pressures of 100–1000 psi. Alternatively, pressure could also be applied by local electromechanical means (electrostatic membranes,[31] electrowetting),[32] but voltage requirements could be impractical in comparison to the simplicity of vacuum actuation. It should also be noted that the scaling effects considered here are mainly due to the change in Laplace pressure, however, one should also keep in mind other microfluidic forces as dimensions are scaled.

It should be mentioned that neither the lifetime nor the switching limit of the devices reported herein were investigated. The intent was to display the principle and fundamental operations of the devices, thus optimization (ideal sealing/localization) was not the key concern. Having mentioned this, if the device fabrication had been optimized, the weakest link would then be the liquid metal and the oxidation thereof. Therefore hermetic sealing is an important issue for non-Hg liquid metals. Lastly, it should also be noted that vacuum in this report is constantly supplied to allow the liquid metal to remain in the confinements. Alternate methods could also be used to hold this state such as a bistable push-button or latching valve.

It has been shown that vacuum actuation can be used to drive liquid metals into microreplicated trenches, and upon release of vacuum, the liquid metal dewets into tiny droplets. As a result, electrical and electromagnetic characteristics can be drastically altered beyond the capability of permanent solid wires interconnected with switches or transistors. Actuation speeds exceeding 30 cm s^{-1} are achievable, and much faster speeds are possible with liquid metal droplet localization. This approach is, in principle, scalable to both small "wire" dimensions (100's of nm) and over very large substrate areas (no practical upper limit). Such capability may be of value for next generation simple electronic switches, tunable antennas, adaptive reflectors, and switchable metamaterials.

The University of Cincinnati authors acknowledge research support from the Air Force Research Laboratory, Contract No. UES-P875-6. They would also like to thank Mr. Hari Atkuri Senior Research Engineer of Gamma Dynamics for his advice and contributions on module sealing. The N.C. State authors acknowledge research support from NSF ECCS 0925797.

[1]F. B. Gross, W. Rinaldi, and S. Green, *Frontiers in Antennas: Next Generation Design & Engineering* (The McGraw-Hill Companies, New York, 2011), p. 277–303.
[2]C. Chung-Hao and D. Peroulis, IEEE Trans. Microwave Theory Tech. **55**(12), 2919 (2007).
[3]D. Y. Kim and A. J. Steckl, Appl. Phys. Lett. **90**(4), 043507 (2007).
[4]J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, and M. D. Dickey, Adv. Funct. Mater. **19**(22), 3632 (2009).
[5]M. R. Khan, G. J. Hayes, J.-H. So, G. Lazzi, and M. D. Dickey, Appl. Phys. Lett. **99**(1), 013501 (2011).
[6]I. E. Khodasevych, C. M. Shah, S. Sriram, M. Bhaskaran, W. Withayachumnankul, B. S. Y. Ung, H. Lin, W. S. T. Rowe, D. Abbott, and A. Mitchell, Appl. Phys. Lett. **100**(6), 061101 (2012).
[7]G. J. Hayes, S. Ju-Hee, A. Qusba, M. D. Dickey, and G. Lazzi, IEEE Trans. Antennas Propag. **60**(5), 2151 (2012).
[8]J. Wang, S. Liu, and A. Nahata, Opt. Express **20**(11), 12119 (2012).
[9]SIGMA-ALDRICH, in *Adobe Reader*, edited by MSDS (SIGMA-ALDRICH, 2011).
[10]W. R. Hunter and R. T. Williams, Nucl. Instrum. Methods Phys. Res. **222**(1–2), 359 (1984).
[11]M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, and G. M. Whitesides, Adv. Funct. Mater. **18**(7), 1097 (2008).
[12]R. J. Larsen, M. D. Dickey, G. M. Whitesides, and D. A. Weitz, J. Rheol. **53**(6), 1305 (2009).
[13]P. Surmann and H. Zeyat, Anal. Bioanal. Chem. **383**(6), 1009 (2005).
[14]L. Tingyi, P. Sen, and C.-J. Kim, J. Microelectromech. S. **21**(2), 443 (2012).
[15]R. H. Busey and W. F. Giauque, J. Am. Chem. Soc. **75**(4), 806 (1953).
[16]F. Aqra and A. Ayyad, Metall. Mater. Trans. B **42**(1), 5 (2011).
[17]W. M. Haynes, *CRC Handbook of Chemistry and Physics*, 92nd ed. (CRC, 2011), pp. 4–121.

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[18]W. M. Haynes, *CRC Handbook of Chemistry and Physics*, 92nd ed. (CRC, 2011), pp 12–41.
[19]Pollard Highway Products, in *Adobe Reader*, edited by MSDS (Pollard Highway Products, 2012).
[20]R. H. Stokes and R. A. Robinson, Ind. Eng. Chem. **41**(9), 2013 (1949).
[21]W. M. Haynes, *CRC Handbook of Chemistry and Physics*, 92nd ed. (CRC, 2011), pp. 4–128.
[22]J. Kestin, H. E. Khalifa, and R. J. Correia, J. Phys. Chem. Ref. Data **10**(1), 71 (1981).
[23]O. Ozdemir, S. I. Karakashev, A. V. Nguyen, and J. D. Miller, Minerals Eng. **22**(3), 263 (2009).
[24]W. M. Haynes, *CRC Handbook of Chemistry and Physics*, 92nd ed. (CRC, 2011), pp. 5–73.
[25]J. Berthier, *Microdrops and Digital Microfluidics* (William Andrew Publishing, 2008).
[26]X. Xu, B. Peng, D. Li, J. Zhang, L. M. Wong, Q. Zhang, S. Wang, and Q. Xiong, Nano Lett. **11**(8), 3232 (2011).
[27]M. G. Pollack, A. D. Shenderov, and R. B. Fair, Lab Chip **2**(2), 96 (2002).
[28]See supplementary material at http://dx.doi.org/10.1063/1.4764020 for discussion of our dosing technique and dipole simulation results (Fig. S1).
[29]M. Maillard, J. Legrand, and B. Berge, Langmuir **25**(11), 6162 (2009).
[30]L. Cao and D. Gao, Faraday Discuss. **146**, 57 (2010).
[31]S. J. Mazlouman, A. Mahanfar, C. Menon, and R. G. Vaughan, in presented at IEEE International Symposium on Antennas and Propagation (APSURSI), 2011.
[32]A. Banerjee, E. Kreit, Y. Liu, J. Heikenfeld, and I. Papautsky, Lab Chip **12**(4), 758 (2012).

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