DEP actuated nanoliter droplet dispensing using feedback control†

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Dielectrophoretic (DEP) droplet dispensing using dielectric-coated coplanar electrode structures provides an ideal platform for testing smart control systems for high-speed microfluidic devices. Open-loop control of DEP droplet dispensing is not sufficiently robust for precision droplet dispensing because unavoidable surface property variations of the substrates and other parameters such as liquid viscosity introduce uncertainty in the motion. Closed-loop systems employing distributed optical sensors and feedback provide flexibility, sensitivity, and reliability. In this new scheme, an array of distributed optical sensors detects fluid motion and, through a programmable control module, triggers application of AC voltage bursts of appropriate magnitude, duration, and frequency to control liquid motion and droplet formation. Reconfiguring the module connections and reprogramming the control module permits testing of a variety of control strategies.

Introduction

Lab-on-a-chip (LOC) technology integrates microfluidics for handling small liquid volumes with miniaturized analytical devices or diagnostic probes for the performance of chemical/biomedical protocols. Microfluidic functionalities essential to a workable lab-on-a-chip include droplet dispensing,1 mixing,2 separation, routing,3 reacting4 and transport. Such systems promise broad application for analysis, diagnostics, and other routine laboratory processes where higher throughput, smaller required volumes of biological substances or reagents, and massively parallel processing are advantageous. Not as often acknowledged is that automation reduces human exposure to dangerous substances and frees up the time of laboratory technicians for more productive labor.

LOC schemes may be broadly categorized according to the microfluidic subsystems that drive them. One broad category relies on mechanical components such as microvalves, micropumps, or even syringes to move liquid through closed channels machined into substrates. The second category employs any of a diverse set of actuation schemes including electrically-, thermally- or optically-generated capillarity,5-8 charge-induced surface wetting,9 electro-osmosis,10,11 electroconvection,12 and electromechanical actuation. Often, such systems do not employ channels at all, but instead use electrode arrays patterned on open substrates, and employ discrete droplets as fundamental operational elements for transport, processing, reacting and other operations.13,14 Electromechanical schemes, principally including electrowetting-on-dielectric (EWOD)15-18 and dielectrophoresis (DEP),19,20 are particularly amenable to such droplet-based microfluidics.

A high degree of integration enhances the capability of any lab-on-a-chip, but concomitantly increases the complexity and raises the technical challenges of how to monitor processes and how to operate systems intelligently. Attention is now turning to real-time feedback control because it offers the promise of smart, automated operation. The few examples of feedback-controlled microfluidics reported in the literature to date include flow-rate control,21-24 temperature-based chemical reaction control,25,26 programmable processor27 and capacitance-sensing based feedback control.28 It is clear that more effort in this area is needed. This paper describes a system using a distribution of optical sensors to control high-speed DEP actuation and droplet dispensing.

DEP actuation and droplet dispensing

The electrode structure for DEP droplet dispensing consists of parallel and coplanar, dielectric-coated electrode strips patterned on an insulating substrate,29,30 see Fig. 1(a). A microliter-sized parent drop is manually deposited at one end, as shown by the dashed circle. When AC voltage at sufficiently high frequency (~100 kHz for DI water) is applied, a finger-like rivulet of semi-cylindrical cross-section forms and extends quickly to cover the electrodes. When this rivulet reaches the far end of the structure, it stops and establishes electrohydrostatic equilibrium. The liquid DEP force is responsible for the rivulet’s extension along the electrodes, but the cross-sectional profile is controlled by capillarity, which completely dominates over gravity. When voltage is removed, the liquid finger breaks up into regularly spaced sessile droplets of fairly uniform size by hydrodynamic instability. In most respects, this instability is identical to that manifested by the cylindrical liquid jet analyzed by Lord Rayleigh over a century ago.31,32 Usually, one droplet forms per length * , where * = 4.508D is the most unstable wavelength, D = 2w + g is the diameter of the cylindrical capillary jet, and w and g are electrode width and gap, respectively. The bumps are spaced at intervals of * , which promotes regular droplet formation, and sized at radius * = 0.946D, so that each bump can accommodate the semi-cylindrical liquid volume trapped per wavelength.33,34
The T-junction with transverse gap \( g' \) overcomes the tendency of surface tension to draw some of the liquid back into the parent drop when the voltage is turned off,\(^{33}\) while imposing negligible impedance on the liquid motion. By first removing the voltage from \( E_2 \), all the liquid along the adjacent sections of the electrodes \( E_1 \) and \( E_3 \) is trapped, preventing backflow and allowing the hydrodynamic instability to proceed undisturbed. The result is more regular and well-spaced droplets.\(^{29,30}\)

For adaptation as a platform to test closed-loop control schemes, the DEP droplet dispenser is coupled through transparent diaphragms to a set of optical fibers mounted under the electrode structure. These diaphragms, depicted as squares in Fig. 1(a), are at the bottom of pyramidal pits fabricated by anisotropic, backside etching of the \(<100> \) Si wafer. Optical fibers, from which the cladding has been stripped, are mounted into these etched pits, carefully aligned normal to the optical windows and secured with epoxy, see Fig. 1(b). The substrates are illuminated from above, so when the leading edge of the finger arrives at a window, it reduces the incident light. The sensing module detects this attenuation.

**Device fabrication and fiber assembly**

The DEP droplet dispenser with optical diaphragms is fabricated on a double-side polished, \(<100> \) Si wafer of thickness \( 550 \pm 50 \) \( \mu \)m. The process, shown in Fig. 2, starts with a 400 Å thermal oxide layer, which improves the strength of subsequent 1800 Å low-pressure chemical vapor deposition (LPCVD) nitride coating. Next, 8 \( \mu \)m of tetraethylorthosilicate (TEOS) glass is deposited on the device side by plasma-enhanced chemical vapor deposition (PECVD) for passivation. The first of two photolithography steps patterns optical windows on the backside of the wafer. After dry etching, the patterned nitride layer serves as a pseudo mask for anisotropic silicon etching in hot 40 wt\% KOH, creating the pyramidal pits for the fibers with square transparent diaphragms (140 by 140 \( \mu \)m) at the bottom. After deposition of 0.2 \( \mu \)m Al on the TEOS layer, a second lithography step patterns the electrode structures, properly aligning them with the optical windows. Then, 0.5 \( \mu \)m spin-on-glass (SOG, Futurrex IC1-200) is spin-coated and thermally cured, followed by a 0.2 \( \mu \)m amorphous fluoropolymer hydrophobic coating (Dupont Teflon-AF™ or Asahi Cytop™). The combination of SOG and fluorocarbon coating provides a robust layer with good dielectric strength and hydrophobicity for reliable and repeatable actuation.

Commercial riser-rated fiber cables (Corning OFNR 50/125\( \mu \)m) are used for signal coupling from the optical windows to the sensing module, see Fig. 1(b). After stripping the jacket, the fiber is seated in the etched pit using a 3-axis micromanipulator and glued with two types of UV-cured epoxy adhesives: Dymax OP-52 with refractive index \( n_{g1} = 1.52 \) and OP-4-20632-GEL with \( n_{g2} = 1.554 \), respectively. The less viscous OP-52 (5000 cP) fills the gap between the diaphragm and the core and minimizes signal loss by matching the refractive indices at the interface. The more viscous OP-4-20632-GEL (50 000 cP) secures the fiber in the etched pit and improves assembly strength.

The optical windows, composed of TEOS, SOG and Teflon layers, are transparent to visible light, but diaphragm thickness and any misalignment of the fiber adversely influence light transmission. The grating aperture of the optical window is...
larger than the numerical aperture of the fiber, \( \sqrt{n_2^2 - n_1^2} = 0.2 \), where \( n_2 \), \( n_1 \) are refractive indices of the fiber core and the cladding. Therefore, the numerical aperture determines the light incident on the optical fiber. Assuming ideal alignment and 50% attenuation due to dielectric absorption and interfacial reflection, we estimate the power received by the photodiode to be \( \sim 2 \) nW.

**Closed-loop feedback control**

The block diagram in Fig. 3 describes the closed-loop system consisting of the DEP device, the optical-sensing elements, and the control module. The microcontroller executes a program directing the function generator to create an AC voltage signal, which is amplified and applied to the DEP chip for liquid actuation. The feedback system includes the optical fibers mounted to the transparent windows beneath the device, which detect the liquid motion. Trigger signals are generated by the sensing module and fed back to the control module, which, complying with programmed instructions, applies voltage bursts of specified magnitude, frequency and duration to control liquid motion.

The control logic is programmed on a PC in PIC-C using a code editor, and then downloaded to the microcontroller (Microchip PICSTAR plus). A LabVIEW macro triggers program initiation, camera recording, and video acquisition simultaneously. The system is very flexible; various control strategies and fluidic functionalities can be implemented easily by modifying and then downloading new programs to the PIC. Results of testing several control strategies are presented later in this paper.

**Sensing and control modules**

The diagram in Fig. 4(a) shows the optical signal sensing circuitry. These signals are detected by a PIN photodiode
(OPF482) operated in the photovoltaic mode to minimize background noise. For photodiode flux responsivity of 0.5 A/W, the optical signal is converted to a photocurrent of ~1 nA, then amplified by a high transconductance amplifier (AD549) to an output level of ~1 V. Cascaded with the low-pass filter (LPF) is a sample-and-hold device that stores a reference value of the optical signal. When this signal drops to <95% of the reference, the comparator generates a trigger signal. Several of these circuits, one for each mounted optical fiber, constitute the sensor array.

Fig. 4(b) shows the diagram of the control module. The Microchip® microcontroller (PIC16F877) monitors trigger signals and, through a D/A converter (MCP4492), directs the function generator (XR2206) to apply a sequence of AC voltage bursts with preset values for voltage magnitude \( V \), frequency \( f \), and maximum duration time \( T \). A comparator guarantees that voltages are switched only at zero crossings and high-speed PhotoMos™ relays are used for voltage on/off control. Program execution is monitored on a dedicated LCD display.

Sensitivity, response speed and noise immunization are major concerns in the design. Dependent on illumination intensity, fiber orientation, electrode spacing, and finger profile, the voltage decrement due to optical attenuation may be expected to range from ~50 to ~200 mV. The time constant of the preamp, ~1 ms, and the response of the PhotoMos relay, 0.2 ms, account for most of the circuit response delay, which is negligible compared to the time scale of DEP actuation, ~10 to ~100 ms. The circuit is housed in a cast metal chassis for EM shielding.

**Experiments**

The experimental electrodes had width \( w = 30 \mu m \), gap spacing \( g = 30 \mu m \), length \( l \approx 10 \text{ mm} \), and T-junction gap spacing of \( g' = 10 \mu m \). The 25 bumps, spaced at \( \lambda = 410 \mu m \), were of radius \( R_0 = 85 \mu m \), giving an estimated droplet volume \( V = 1.3 \, \text{nL} \). DI water (dielectric constant \( \kappa_1 = 80 \), conductivity \( \sigma_1 = 1.5 \times 10^{-4} \, \text{S} \, \text{m}^{-1} \), and surface tension \( \gamma = 0.073 \, \text{Nm}^{-1} \)) was used exclusively. Bipolar AC voltage bursts of ~250 to ~400 V-rms in the frequency range of 70 to 100 kHz were applied to the electrode pairs.

A high-speed camera (Photron FASTCAM-PCI) mounted on a stereomicroscope (Zeiss Stemi V6) recorded all experiments at 500 fps. A 150 W tungsten-halogen light source was used as illumination. To increase the video contrast, the optics was set up a stereomicroscope (Zeiss Stemi V6) recorded all experiments at 500 fps. A 150 W tungsten-halogen light source was used as illumination. To increase the video contrast, the optics was set up an axial, diffuse beam-splitter to establish uniform illumination over a 5 × 5 cm² area. Videos were processed using a MATLAB™ program to track the leading edge of the moving finger.

A block diagram of the experimental implementation of the closed-loop feedback system is shown in Fig. 5. Amplified, bipolar voltage is supplied on the DEP microdispenser with negative polarity to the electrode E1 and positive polarity to E2 and E3, respectively, as shown by the thin arrows. Up to four sensors can be implemented, shown by block arrows in feedback path II. One of the sensors is connected to the normally closed relay unit through feedback path I for operation of E2.

**Droplet dispensing results using a single sensor**

The flow chart in Fig. 6 outlines a control program implementing a single sensor and two voltage bursts applied in sequence. Upon initiation (a), the control module applies the first voltage burst \( (V_1, f_1, T_1) \) between E1 and E2/E3 for liquid actuation (b), and then monitors the sensor \( S \) (c). If no signal is detected (that is, \( S = 0 \)) within preset maximum time \( T_1 \), the program stops, displays ‘Failure’, and the voltage is removed. If the sensor is triggered within \( T_1 \), \( S = 1 \), the feedback control directs the relay controller (feedback path I) to remove voltage for E2, thus trapping the liquid along E3 (d). Simultaneously, the feedback signal triggers the control module (feedback path II) to apply the second burst \( (V_2, f_2, T_2) \) to maintain the finger profile and to prevent any further lengthening of the finger. After elapsed time \( T_2 \) (e), the control module removes the voltage from E3 (f), allowing droplets to form, and reports ‘Success’ (g).

**Fig. 5**  Block diagram of the feedback control system with the voltage application path shown with thin arrows and two feedback paths with block arrows. Up to four sensors may be implemented, one of which is connected to the relay controller.

**Fig. 6**  The flow chart shows the control strategy of single-sensing feedback control. (a) Initiation. (b) First voltage burst initiates liquid actuation. (c) The monitored sensor is designated \( S \). If the leading edge of the rivulet is not detected within \( T_1 \), execution stops. (d) If \( S = 1 \), the voltage to E2 is removed to initiate liquid trapping, and simultaneously the second burst is applied to E3. (e) The timer counts down \( T_2 \). (f) The voltage is removed from E3 for droplet dispensing. (g) The system reports ‘Success’.
The images in Fig. 7 show a series of experiments on a set of identical DEP structures with dimensions \( \frac{w}{g/g_0} = 30/30/10 \) mm. Optical fibers are mounted at three locations S1, S2, and S3 along the electrodes as marked by arrows. Two voltage bursts, both at 80 kHz, are applied sequentially. In separate experiments using S1, S2, or S3 as the active sensor, three different initial voltage magnitudes, 293, 304, and 316 V-rms, were tested. These voltages were chosen to be high enough to avoid perceptible retardation at the T-junction. The second burst, of duration \( T_2 = 30 \) ms and always at an amplitude 325 V-rms, equalized the distribution of trapped liquid along the length of the structure without further extension of the rivulet. 

At \( V_1 = 293 \) V-rms in Fig. 7(a-1), the leading edge triggered the sensor S1 and the feedback control removed the voltage from E2 to trap the liquid mass; meanwhile, \( V_2 = 325 \) V-rms was applied between E1 and E3. After \( T_2 = 30 \) ms, the finger broke into two droplets, instead of one as expected, due to a triggering delay inherent in the controller. Voltages of \( V_1 = 304 \) V-rms in Fig. 7(a-2) and 316 V-rms in Fig. 7(a-3) also produced an extra droplet. Droplet volumes were slightly larger than at 293 V-rms, probably due to a weak but evident dependence of the rivulet’s diameter upon voltage.

For experiments conducted using S2 as the active sensor [see Fig. 7(b)], the feedback control performed similarly, yielding four droplets as predicted. For tests using S3 [Fig. 7(c)], the number of dispensed droplet was close to the prediction of 13 with a maximum error of \( \pm 2 \), possibly due to the formation of tiny satellite droplets. These experiments demonstrate that a control strategy based on a single sensor can control the trapped finger length and thus the number of dispensed droplets.

Fig. 8 plots transient finger length data extracted from the experiments in Fig. 7 with \( z(t) \) measured from the T-junction gap. The data reveals smooth motion with little apparent retardation at the T-junction gap. The solid markers indicate the time when the optical sensor (S1, S2, or S3) detects arrival of the leading edge of the finger while the last plotted point for each set indicates when the voltage was removed to initiate droplet formation.

Because sensor S3 is much further away from the parent drop than S1 or S2, the amplitude of the first voltage burst strongly influences the arrival time of the finger. For example, changing the voltage from 293 to 316 V-rms decreases the trigger time from 85 to 40 ms. Triggering delays lead to some overshoot at 316 V-rms when either S1 or S2 are active. On the other hand, no overshoot or length extension occurs for S3 active, probably because the rivulet is moving much slower by the time it reaches S3. Fig. 8 reveals that sensor location controls the number of droplets dispensed, irrespective of variations of parameters such as voltage, initial placement of the parent drop, liquid viscosity, and flow retardation at the T-junction. Fig. 9 is a histogram of

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**Fig. 7** Experimental demonstration of feedback-controlled droplet dispensing for three different sensor locations: S1, S2, and S3 (marked by the arrows) for each of the three different initial voltage burst magnitudes (293, 304, 316 V-rms). The magnitude of the second burst is 325 V-rms for all experiments.

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**Fig. 8** Composite plot of the position of the leading edge of the finger \( z(t) \) for the single-sensor feedback control scheme of Fig. 7. The data are obtained for three sensor locations: S1, S2, and S3, and for three different values of the amplitude of the first voltage burst: 293 V, 304 V, and 316 V, all in rms values. The solid points indicate the time when the finger was detected by the sensor and the last plotted points mark the time when the voltage was removed to form droplets.
results for the structure shown in Fig. 7, for many trials performed with the structure of Fig. 7 using the three different active sensor locations. The time-based control strategy shows reasonable repeatability. In general, the number of droplets dispensed is within $1/C_6$ of the expected value.

The largest deviation from the expected number of droplets, encountered when S1 is active, is probably due to triggering delays and fluid momentum. For the active sensor located at S2, an ‘elastic’ response related to surface tension during the finger trapping stage may cause an observed, modest shortening of the rivulet. For location S3, satellite droplet formation may lead to fewer dispensed droplets.

Fig. 10 plots another important performance measure of the feedback-controlled dispensing scheme, the volumes of the dispensed droplets. These values were calculated from measured radii based on the assumption of hemispherical shapes. Higher actuation voltages create wider liquid fingers, which, according to Rayleigh’s theory, produce fewer droplets of larger volume. The scatter of the volume data is accentuated because volume is proportional to the third power of the measured droplet radii.

Model predictive feedback control using multiple-sensors

One means for control of distributed systems such as the DEP-based droplet dispenser is to implement model predictive feedback control. The basis of this approach is to monitor the system, comparing its performance in real-time to a reference derived from an existing model and then to apply corrections on the fly to drive the system back toward the desired dynamic trajectory. For our system, we can use the set of optical sensors distributed along the structure. When a sensor detects passage of the leading edge of the rivulet, the signal is sent to the microcontroller, which compares the arrival time to the value predicted by the model. The voltage is then adjusted upward or downward to maintain $z(t)$ as close as possible to the desired trajectory. See Fig. 11, which is illustrative.

The first step to implement model predictive control is to develop a reduced-ordered, hydrodynamic model of DEP finger actuation dynamics. Assuming the rivulet cross-section is constant, the non-linear equation of motion is

$$
\pi\left(\frac{w}{2} + g\right)^2 \rho \frac{d}{dt} \left(\frac{dz}{dt}\right) + 4\mu \frac{dz}{dt} + \frac{4}{3}(w + g)\frac{dz}{dt} = UV^2 u(t) - \pi\left(\frac{w}{2} + g\right)\gamma
$$

(1)

where $\mu =$ dynamic viscosity, $\xi =$ contact-line-friction coefficient, $\gamma =$ surface tension, $\rho =$ liquid density, and $u(t) =$ unit step function. The left-hand side of eqn (1) includes the time rate of change of momentum, a viscous drag term (obtained from a conformal mapping analysis of the laminar flow model of the finger36), and the contact line friction force. This last term is associated with energy dissipation caused by molecular kinetics.37 The coefficient $\xi$ is determined from a curve-fitting exercise.38 On the right-hand side of eqn (1) appear the DEP force...
that drives the rivulet starting at $t = 0$, and the constant capillary force, which always tends to pull the finger back.

A full test of the scheme, with the voltage recomputed and adjusted after comparison of the trajectory to the reference, could not be implemented because of the memory limits of the microprocessor. However, a realistic test was conducted by using simulations done in advance using SimuLink™ and with the magnitudes of a voltage sequence (316, 270, 293, and 283 V-rms) programmed into the control logic. Fig. 12 shows selected video frames from a test with three distributed sensors: S1, S2, S3. The first voltage burst of 316 V-rms was applied at $t = 0$. At 6 ms, the finger arrived at the sensor S1, triggering the second burst of 270 V-rms, which decelerated the rivulet. When sensor S2 was triggered the controller at 18 ms, the third voltage burst (293 V-rms) was applied, accelerating the rivulet. Finally, when the rivulet reached S3 at 58 ms, the voltage on E2 was removed trapping the liquid finger and the fourth voltage burst of 283 V-rms was applied between E1 and E3. The frequency was fixed at 80 kHz.

The fourth and last voltage burst was set at a relatively low value to promote even distribution of the trapped liquid inventory along the length of electrode E3 before droplet formation. Note that, at 110 ms [see Fig. 12(e)], the left side of the finger has passed out of the field of view. The droplets that formed after voltage removal are irregular due to deterioration of the SOG/Teflon coating that occurred after more than twenty tests had been conducted with this particular substrate.

Transient finger length data obtained using the three sensors, S1, S2, and S3, are plotted in Fig. 13. The continuous curve is a solution of eqn (1) at $V = 295$ V-rms. The experimental trajectory remains fairly close to the reference; the rapid accelerations and decelerations evident when the finger reaches each sensor demonstrate the rivulet’s response to voltage-based control. Because momentum is negligible, each section of the data can be fitted by least-squared regression to the hydrodynamic model of eqn (1) with the contact line friction coefficient $\xi = 0.314$ Ns m$^{-2}$. This experiment demonstrates that model predictive feedback control with distributed sensors is capable of error detection and correction, and should be a suitable real-time control strategy for high-speed microfluidic systems.
Conclusion

Liquid DEP microactuation offers fast dispensing of droplets ranging in volume from ~10 pL to ~100 nL within ~100 ms. The three-electrode microdispenser design, featuring the T-junction to trap liquid, facilitates droplet uniformity. Coplanar structures capable of dispensing as many as 30 droplets per structure have been demonstrated and larger numbers should be possible. In fact, scale-up to thousands of droplets should be possible using chips patterned with multiple structures in parallel on a single chip. Still, successful development of such complex, high-speed microfluidic systems will depend on a high level of controllability. Some form of closed-loop process control will be essential. Another reason for considering feedback is to overcome inherent performance limits caused by irregularities in chip processing, surface contamination, and the need to accommodate liquids of varied viscosity.

The feedback controlled microfluidic scheme reported here proves that high-speed DEP actuated droplet dispensing can be controlled effectively by modulating the AC voltage in response to sensor inputs. The distributed optical fibers along the length of the electrode structure detect the leading edge of the advancing liquid rivulet. These signals are used in real-time to modify the applied voltage according to a model predictive control strategy. The controller compares the arrival time of the liquid at each sensor location to a set of previously established reference values and then adjusts the voltage upward or downward according to a set of instructions to speed up or slow down the liquid, respectively.

Two control schemes have been demonstrated. The first employs a single sensor and shows that a predetermined volume of liquid can be dispensed, then trapped and maintained stably by voltage. This scheme provides a simple means to improve the accuracy and reliability of DEP droplet dispensing. The second scheme employs three sensing elements, and uses the model predictive control strategy to control the liquid motion along its trajectory. By comparing the measured time with the reference time, the system generates a sequence of corrective voltage bursts to control the motion of the rivulet. But, while model predictive control offers great promise for real-time control this DEP droplet dispensing platform in LOC devices, one may envision a far wider variety of control strategies for automatic processing and intelligent handling of picoliter to nanoliter liquid volumes. This capability stems from the fact that both the magnitude and frequency of the voltage bursts can be modulated. For example, precise control of the onset of the Rayleigh instability that forms the droplets might be achieved by voltage modulation after the liquid finger has reached the end of an electrode structure. Assuming the liquid contains biological particles such as cells, proteins, or DNA fragments, or possibly tagged polymer marker particles, another idea is to modulate the frequency of the drive voltage, or to superimpose AC signals at multiple frequencies, to effect separation of the particles based on their dielectrophoretic spectra, using a flow fractionation system.]

The configuration of the sensors – optical fibers mounted the backside of the chip and coupled to phototransistors – is less than ideal. In an integrated design, the fibers could be replaced by phototransistors fabricated in the Si wafers beneath the electrodes. Nevertheless, we believe the workability of using distributed sensor elements and model predictive control has been demonstrated. Another limitation of the present work is that we have provided no demonstration of the means to move and manipulate the droplets once they have been dispensed. However, Chugh and Kaler have quite recently reported an integrated scheme to achieve controllable transport of droplets dispensed by DEP, based on the novel oscillatory droplet transport scheme of Gunji and Washizu.

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