Discrete Control of Liquid Drops on a Surface Using Electrowetting

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Claremont GRADUATE UNIVERSITY

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5th International Meeting on Electrowetting

Rochester Museum and Science Center
Rochester, NY (US)
31 May to 2 June, 2006

http://www.ece.rochester.edu/users/jones/EW2006/

R. Mukhopadhyay, *Analytical Chemistry* (March 1, 2006).

Droplet Microfluidics: Features

- Uses the most dominant force present at small scales (interfacial tension) to accomplish aliquoting, dilution, mixing, separation, and transport of liquids.
- Avoids complex, costly design of micro-valves and micro-pumps in micro-channels.
- Controls drop motion by electrostatic actuation, changing the local contact angle at the 3-phase contact-line via "electrowetting."
- Provides a platform re-configurable in software.

Related Work

- Bruno Berge, Lyon, France
  - http://www.varioptic.com
- Richard B. Fair, Duke
  - http://www.ece.duke.edu/Research/microfluidics/
- Chang-Jin "CJ" Kim, UCLA
  - http://cjmems.seas.ucla.edu
- Philips Research Labs, Eindhoven
  - http://www.philips.com (Prins, Hayes, …)
- Frieder Mugele, University of Twente
  - Mugele & Baret, *J. Phy. Condens. Matter*, **17**, R705 (2005)

Forces in Microfluidics

Scales: $V = 1 \text{ cm/s} \quad \ell = 100 \ \mu\text{m}$

Bond Number $\text{Bo} = \frac{\rho g \ell^2}{\gamma} \approx 10^{-3}$

Capillary Number $\text{Ca} = \frac{\mu V}{\gamma} \approx 10^{-4}$

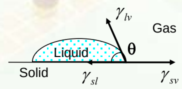
Weber Number $\text{We} = \frac{\rho \ell V^2}{\gamma} \approx 10^{-4}$

⇒ Surface Tension Dominates

Electrowetting on Dielectric (EWOD)

Young's eqn:

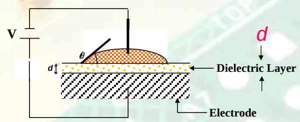
$$\gamma_{sv} = \gamma_{lv}\cos(\theta) + \gamma_{sl}$$



When potential V is applied:

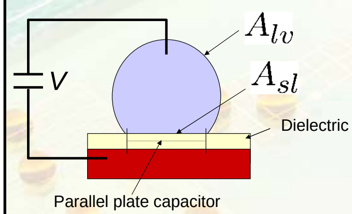
$$\cos\theta(V) = \cos\theta(0) + \frac{\varepsilon_o\varepsilon_r}{2d\gamma_{lv}}V^2$$

Young-Lippmann



Physics of Electrowetting

[cf. Shapiro *et al*, *J Appl Phys*, **93**, 5794 (2003)]



$$Q = (cA_{sl})V$$

$$c = \frac{\varepsilon_o\varepsilon_r}{d}$$

$$E = \gamma_{lv}A_{lv} + (\gamma_{sl} - \gamma_{sv})A_{sl} + \frac{1}{2}(cA_{sl})V^2 - VQ$$

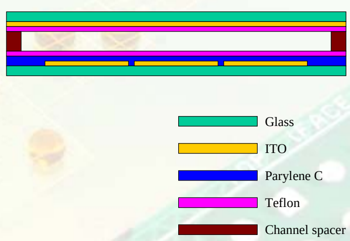
P.E. of external charging source

Minimize *E* to obtain the Young-Lippmann Eqn:

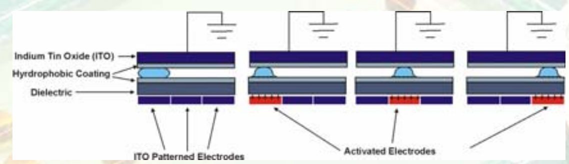
$$\gamma_{lv}\cos(\theta) = \gamma_{sv} - \gamma_{sl} + \frac{\varepsilon_r\varepsilon_o}{2d}V^2$$

Electrowetting Chip Design

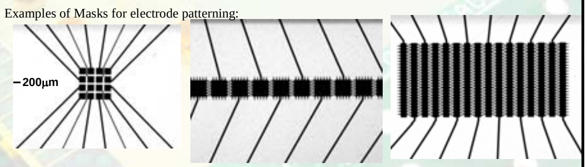
Patterned via photolithography



Discrete Drop Control by EWOD

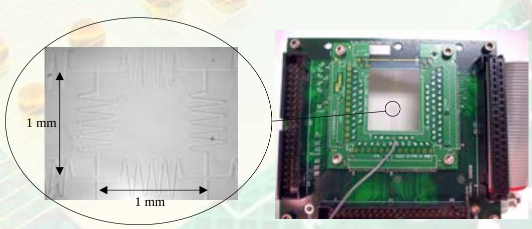


Examples of Masks for electrode patterning:



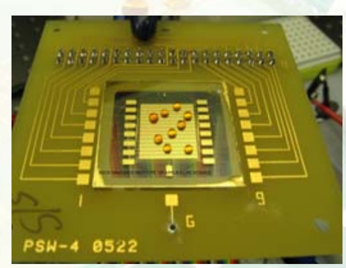
Electrode Array

- Electrodes: Indium Tin Oxide (ITO) or Chromium/Gold
- Dielectric: Parylene C
- Hydrophobic Coating: Teflon



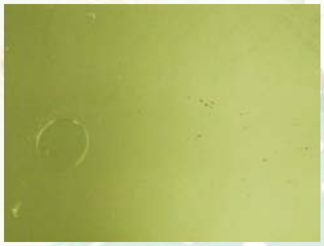
Control and Imaging

- LabView control of electrode potentials
- 40-ch Keithley-2700 controller
- Contact angle goniometer
- Cohu 2200 CCD camera
- National Instruments PCI-1411 frame grabber



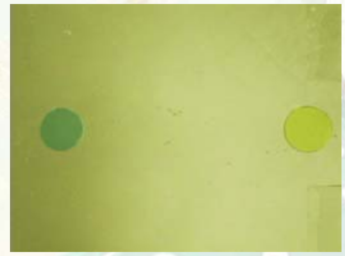
Control of 2-D Movement

- 200 µm gap between top and bottom plates
- 100 mM KCl drop
- 0.5 µL drop volume
- 0.4 second electrode pulse duration
- 60 V (rms) AC
- 8 kHz frequency



Combine and Mix Two Drops

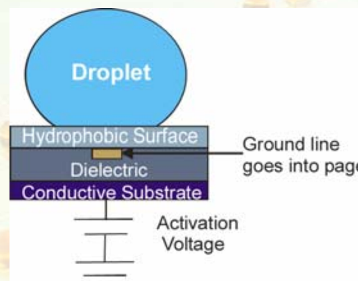
- 200 µm gap between top and bottom plates
- 100 mM KCl with blue or yellow dye
- 0.5 µL drop volumes
- 0.2 second electrode pulse duration
- 60 V (rms) AC
- 8 kHz AC frequency



Combine and Mix Two Drops

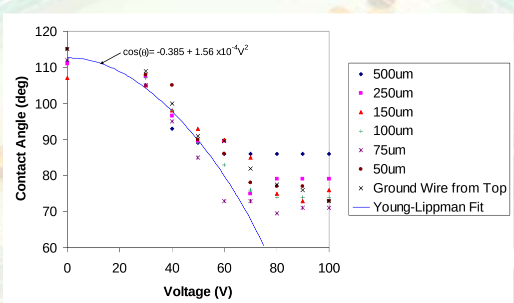
- 65 µm gap between top and bottom plates
- 100 mM KCl drops
- 0.3 µl drop volumes
- 0.5 sec electrode pulse duration
- 60 V (rms) AC
- 8 kHz AC frequency

Grounding from Below



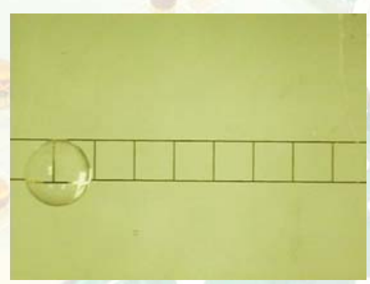
Cooney, Chen, Emerling, Nadim & Sterling, *Microfluidics & Nanofluidics* (2006).

Contact Angle vs. Voltage while Grounding from Below

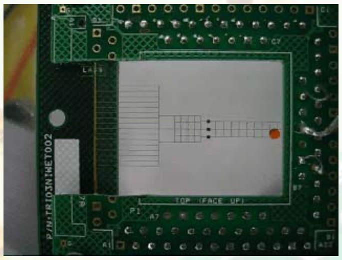


Drop Movement Across Single Surface

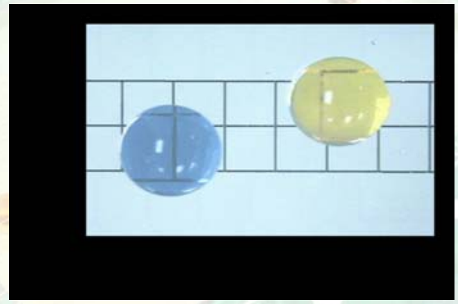
- No top plate!
- **Grounding from below (with gold lines)**
- 3.5 µL drop



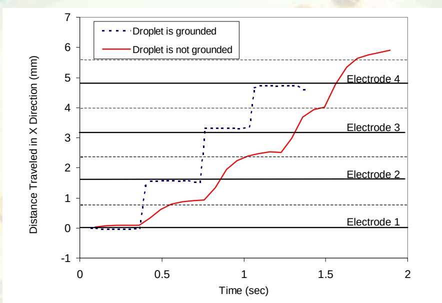
Race Track!



Coalescence w/o Top Plate

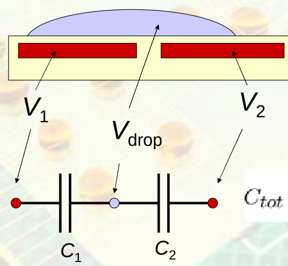


Drop Trajectory w/ and w/o Grounding



Lumped Model: Un-Grounded Drop

$$E = \frac{1}{2}C_1(V_1-V_{dr})^2+\frac{1}{2}C_2(V_{dr}-V_2)^2 = \frac{1}{2}C_{tot}(V_1-V_2)^2$$



C_1 and C_2 proportional to wetted areas

$$V_{drop} = \frac{C_1V_1+C_2V_2}{C_1+C_2}$$

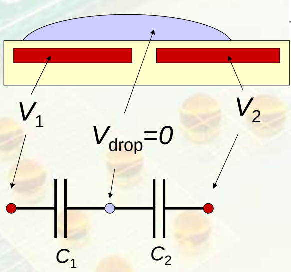
$$x = A_1/A_{tot}$$

$$C_{tot} = A_{tot}\frac{\varepsilon_o\varepsilon_r}{d}\left(\frac{1}{x}+\frac{1}{1-x}\right)^{-1}$$

Maximum C at $x = 1/2$

Lumped Model: Grounded Drop

$$E = \frac{1}{2}C_1(V_1)^2+\frac{1}{2}C_2(V_2)^2$$



C_1 and C_2 proportional to wetted areas

$$x = A_1/A_{tot}$$

Minimum E at $x = 1$ when $|V_1| > |V_2|$

$$E_{elec} = -\frac{A_{tot}}{2}\frac{\varepsilon_o\varepsilon_r}{d}\left[xV_1^2+(1-x)V_2^2\right]$$

Snail-like Translation under AC Forcing

Case I:
50 VAC forcing at *60Hz*
Play back at 30 fps (8000 fps recording)
Propagation of wave during transition

Case II:
50 VAC forcing at *200Hz*
Play back at 30 fps (8000 fps recording)
Propagation of wave during transition

Case III:
50 VAC forcing at *400Hz*
Play back at 30 fps (8000 fps recording)
Propagation of wave during transition

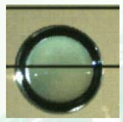
Case IV:
50 VAC forcing at *800Hz*
Play back at 30 fps (8000 fps recording)
Propagation of wave during transition

1 mm

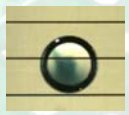
Mixing in a 10-µL Droplet by EW

Effect of applying AC forcing in contact angle variation
•50 VAC forcing at *60Hz* applied for 0.4s to 4 electrodes
•Forcing applied for 0.4 second
•Play back at 10 fps (500 fps recording)

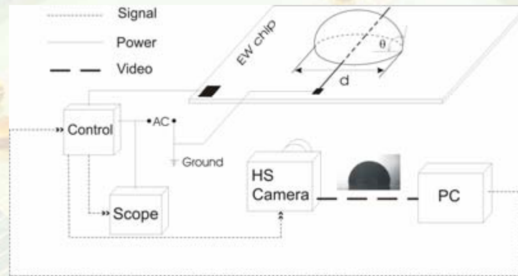
Effect of applying AC forcing in mixing
•50 VAC forcing at *200Hz* applied for 0.4s to 4 electrodes
•Play back at 10 fps (125 fps recording)
•Bottom view of the droplet (eliminates most of the optical distortion)



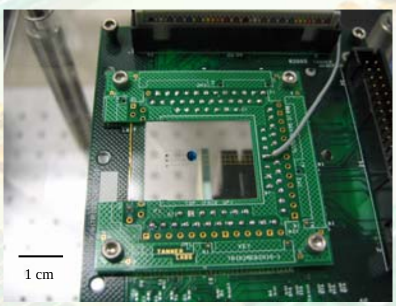
Effect of number of electrodes in mixing
50 VAC forcing at *200Hz* applied for 0.4s to 4 electrodes
Play back at 10 fps (125 fps recording)
Bottom view of the droplet (eliminates most of the optical distortion)



Shape Oscillations of Sessile Drops



Sessile Droplet Oscillations



Visualization (microscope)

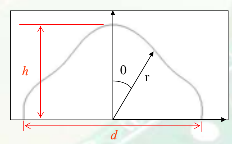
Visualization (HS Camera)

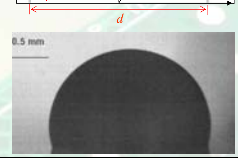
Data Extraction and Analysis

Detecting droplet oscillation modes via image processing (edge detection) → Dynamics of contact angle change (Lippmann's equation)

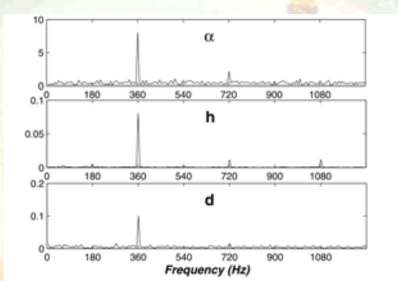
Detecting droplet oscillation modes via image processing (edge detection) → Oscillation shape modes → Potential flow inside the droplet

- Measure EW forcing (scope measurements)
- Synchronize hardware
  Correlate voltage and contact angle
- Apply edge detection algorithms
- Obtain signals for h, d and α
- Power spectra in h, d and α
- Legendre polynomials fit for $r = f(\theta)$



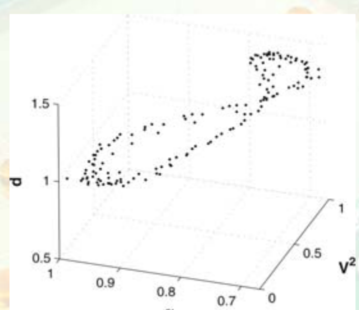


Power Spectrum



Power spectrum obtained via Fast Fourier Transform, of the contact angle, droplet height and diameter time series of a 7 µL droplet of 10% KCl on EWOD chip. Forcing frequency was 180 Hz.

Low-Dimensional Phase Portrait

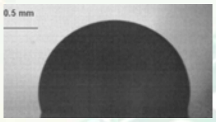


Phase diagram of diameter, forcing voltage squared and dynamic contact angle of a 7 µL droplet of 10% KCl on EWOD chip.

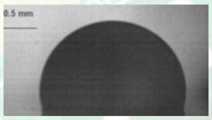
Oscillations at Various Frequencies

50 V forcing at 30 Hz applied for 0.4 sec. Playback at 15 fps (2000 fps record).

50 V forcing at 100 Hz applied for 0.1 sec. Playback at 15 fps (4000 fps record).

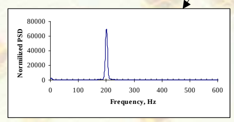


50 V forcing at 300 Hz applied for 0.1 sec. Playback at 15 fps (4000 fps record).

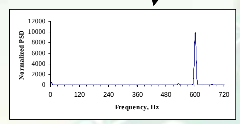


Power Spectra of Shape Modes

$$r = f(\theta) = a_0 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta) + a_6 P_6(\cos\theta) + a_8 P_8(\cos\theta)$$



a_4 is dominant with 100Hz forcing



a_8 is dominant with 300Hz forcing

Application to a Novel Amplification Technology (EXPAR)

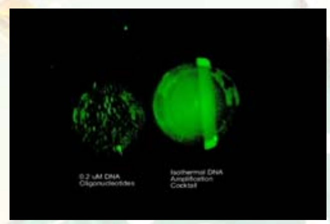
Exponential Amplification Reaction (EXPAR)
(Van Ness, Van Ness and Galas, *PNAS* 100(8):4504-4509, 2003)

- A new nucleic acid amplification and detection platform
  - Small sequences (~6-18 bases)
  - Isothermal (55-65°C)
  - 10^6 to 10^9 fold amplification
  - Extremely rapid (~5 minute chain reaction)
  - No tags or labels needed
- Multiple readouts
  - Mass spectrometry - *research*
  - Real time or end-point fluorescence – *lab or field*
  - Surface spots (several methods) – *lab or field*

Electrowetting Initiated EXPAR Reaction

•Template: 5'–CCT CAT CGC GGG CTT CGA CTC CCT CAT CGC GGG–3'
•Trigger: 5'–CCC GCG ATG AGG–3'

- Dielectric: Polyimide
- Surface: Self-Assembled Monolayer (SAM) and Teflon AF over gold line
- Voltage: 50 V DC
- Volume: 20 μL each
- Fluorescence Microscope: 488nm excitation, 560nm LP emission
- Play Speed: 0.06X for the first 10 seconds, 1.2X for the rest



Conclusions

Advantages of Electrowetting

- Scalable
- No channels, pumps or valves
- Transparent substrate
- Inexpensive to manufacture
- Low electrical energy requirements
- Applicable to protein / DNA assays

http://microfluidics.kgi.edu