Discrete Control of Liquid Drops on a Surface Using Electrowetting

Ali Nadim
Keck Graduate Institute
& Claremont Graduate University
Claremont, CA 91711
nadim@kgi.edu or ali.nadim@cgu.edu

Acknowledgments
• James Sterling
• Reza Miraghaie
• Anna Hickerson
• Christopher Cooney
• Chao-Yi ‘Richard’ Chen
• Jie Dai
• Eve Fabrizio
• Robert Doebler
• Michael Eimerling
• Yousuf Daineshhood
• Maged Ismail
• Alex Wu
• Peter Qu
• Anita Kaka

Funding: NIH SBIR I & II, DARPA, HSARPA, W.M. Keck Foundation
Tanner Research, Ionian Technologies, Northrop Grumman, SAI

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

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.

Forces in Microfluidics

\[ \begin{align*}
V &= 1 \text{ cm/s} \\
\ell &= 100 \mu m \\
\text{Bond Number} \quad &B_0 = \frac{\rho g \ell^2}{\gamma} \approx 10^{-3} \\
\text{Capillary Number} \quad &Ca = \frac{\mu V}{\gamma} \approx 10^{-4} \\
\text{Weber Number} \quad &W_0 = \frac{\rho V^2}{\gamma} \approx 10^{-4} \\
\end{align*} \]

Surface Tension Dominates
**Electrowetting on Dielectric (EWOD)**

Young's eqn:

\[ \gamma_{sd} = \gamma_{lv} \cos(\theta) + \gamma_{sl} \]

When potential \( V \) is applied:

\[ \cos(\theta(V)) = \cos(\theta(0)) + \frac{\varepsilon_0 E^2}{2 \varepsilon_{lv}} V^2 \]

Young-Lippmann

**Physics of Electrowetting**

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

\[ Q = (cA_d)V \]

Parallel plate capacitor

\[ E = \gamma_{lv} A_{lv} + (\gamma_{sd} - \gamma_{lv}) A_{sl} + \frac{1}{2} (cA_d) V^2 - VG \]

Minimize \( E \) to obtain the Young-Lippmann Eqn:

\[ \gamma_{lv} \cos(\theta) = \gamma_{lv} - \gamma_{sd} + \frac{\varepsilon_0 E^2}{2 \varepsilon_{lv}} V^2 \]

**Electrowetting Chip Design**

Patterned via photolithography

- Glass
- ITO
- Parylene C
- Teflon
- Channel spacer

**Discrete Drop Control by EWOD**

**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


Contact Angle vs. Voltage while Grounding from Below

![Image of contact angle vs. voltage graph]

- Young-Lippman Fit:
  \[ \cos(\theta) = -0.385 + 1.56 \times 10^{-4} V^2 \]

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

Lumped Model: Grounded Drop

Snail-like Translation under AC Forcing
Mixing in a 10-µL Droplet by EW

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

**Effect of applying AC forcing in mixing**
- 50 V AC forcing at 200Hz applied for 0.4s to 4 electrodes
- Forcing applied for 0.4 second
- Playback 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 V AC forcing at 200Hz applied for 0.4s to 4 electrodes
- Forcing applied for 0.4 second
- Bottom view of the droplet (eliminates most of the optical distortion)

Shape Oscillations of Sessile Drops

Data Extraction and Analysis

- 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(θ)

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.**

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 recorded).

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

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

Power Spectra of Shape Modes

\[ r = f(\theta) = a_0 + a_1 \cos \theta + a_2 \cos 2\theta + a_4 \cos 4\theta + a_8 \cos 8\theta \]

\( a_4 \) is dominant with 100 Hz forcing.

\( a_8 \) is dominant with 500 Hz 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

- 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