Controlling Spreading and Superspreading using Liquid Dielectrophoresis

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Public Understanding website: http://www.naturesraincoats.com/

Overview

1. Fundamentals: Liquid Dielectrophoresis
   - Interface Localized Dielectrophoresis
   - Films and Droplets
2. Statics: Experiments
   - Films: Shaping Interfaces
   - Droplets: Dielectrowetting
3. Dynamics: Theory and Experiment
   - Three Programmable Spreading Regimes
   - Partial, Complete and Superspreading

Fundamentals: Liquid Dielectrophoresis

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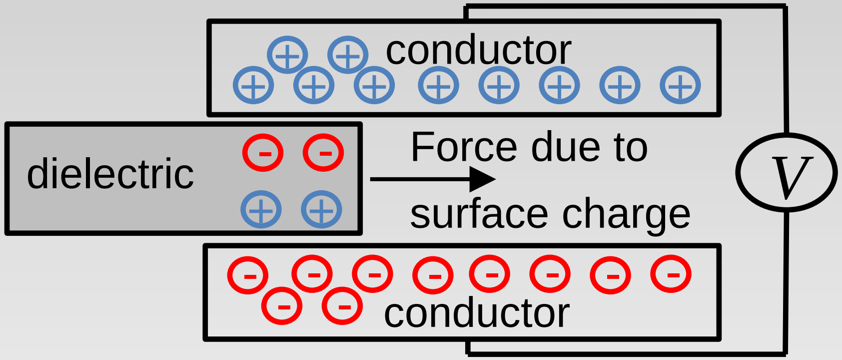
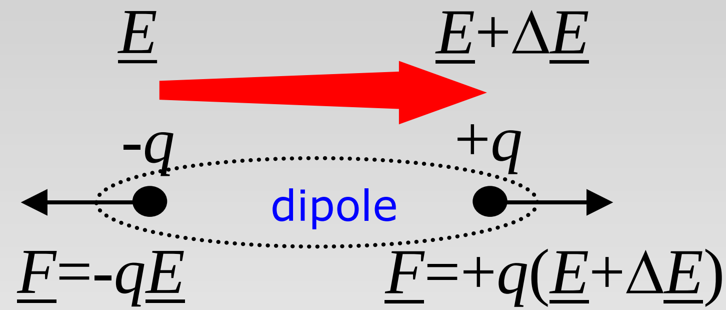
Principles of Dielectrophoresis

Dielectrophoretic Actuated Motion



Dipole in a Non-Uniform Electric Field

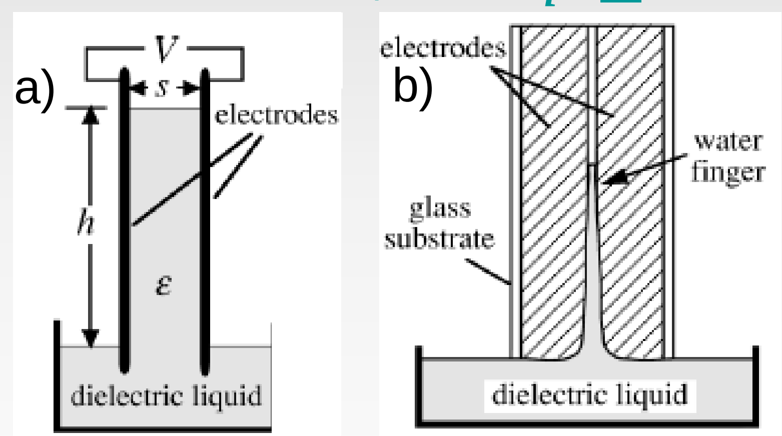


Net force on dipole = $+q\Delta \underline{E}$

Dielectric Liquids

a) Pellat's classic dielectric height of rise experiment

b) Jones' co-planar electrodes with high frequency experiment



Liquid dielectrophoresis[1] - In a dielectric liquid a non-uniform electric field causes liquid motion

References Jones, T. B., *et al.*, Science (1971) 174 1232.
Jones, T. B., Langmuir (2002) 18 4437; J. Appl. Phys. (2001) 89 1441.

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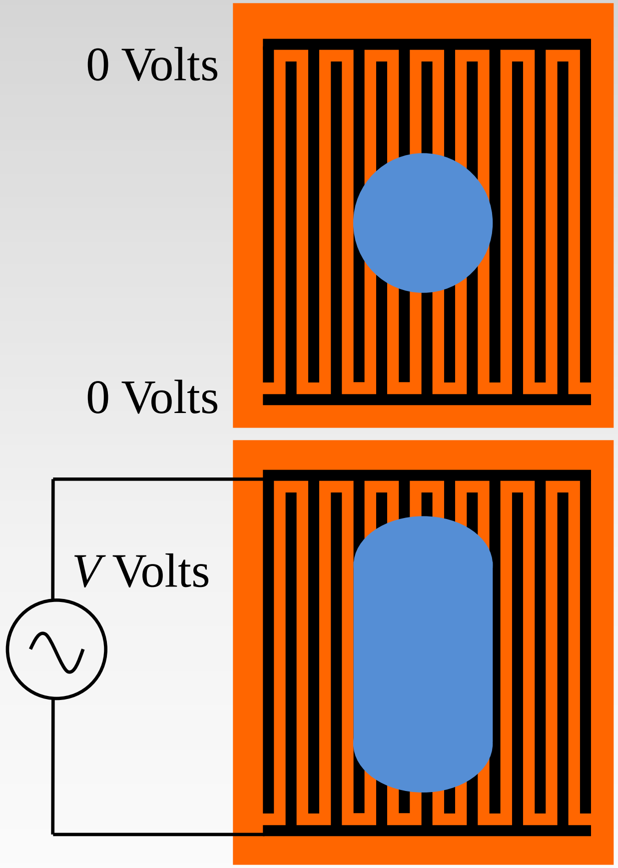
Interface Localized Liquid Dielectrophoresis

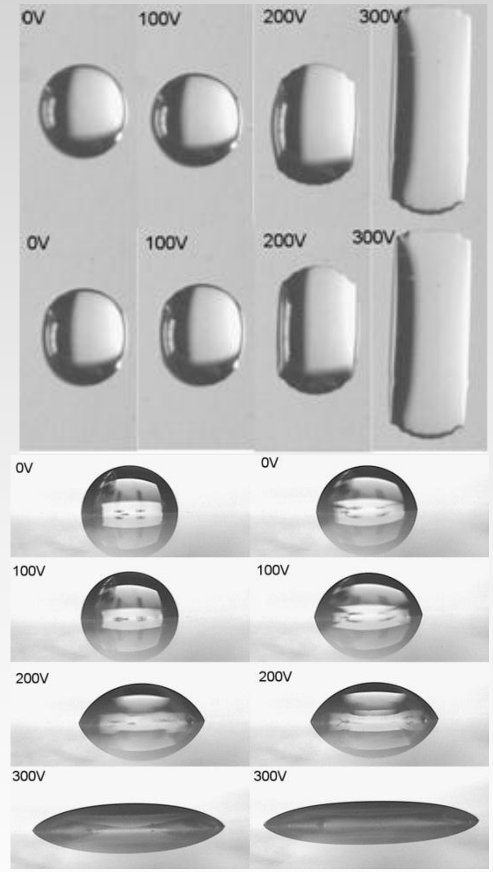
Interdigitated Electrodes

Top view



1,2 PPG Droplet

Top and side views



Key Idea

Non-uniform field decaying away from the substrate localizes liquid dielectrophoresis (L-DEP) to the solid-liquid interface

i.e. becomes a driver of spreading and wetting

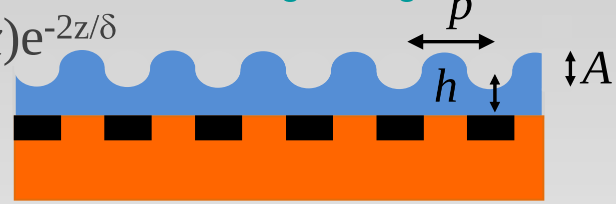
Can also design effects to be localized to a liquid-vapor or liquid-liquid interface

Films and Droplets

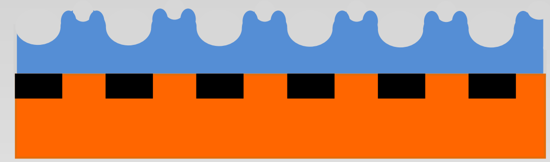
Films

$V = V_o \cos(kx) e^{-2z/\delta}$

Increasing voltage



Higher voltage

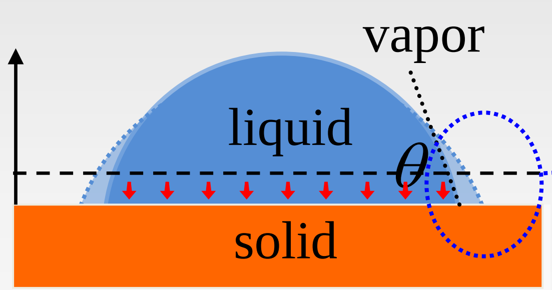


Scaling of amplitude with film thickness and electrode periodicity:

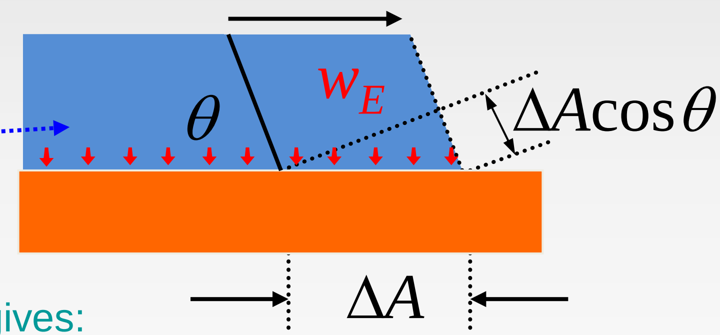
$$\boxed{A = kV^2 \exp(-2\pi h/p)}$$

Droplets

$V = V_o e^{-2z/\delta}$



displace liquid surface



Assuming thick droplet, change in energy balance gives:

$$\Rightarrow \quad \boxed{\cos\theta_e(V) = \cos\theta_e(0) + (\varepsilon_l - 1)\varepsilon_o V^2 / 2\delta\gamma_{LV}}$$

L-DEP Modified Young's Law

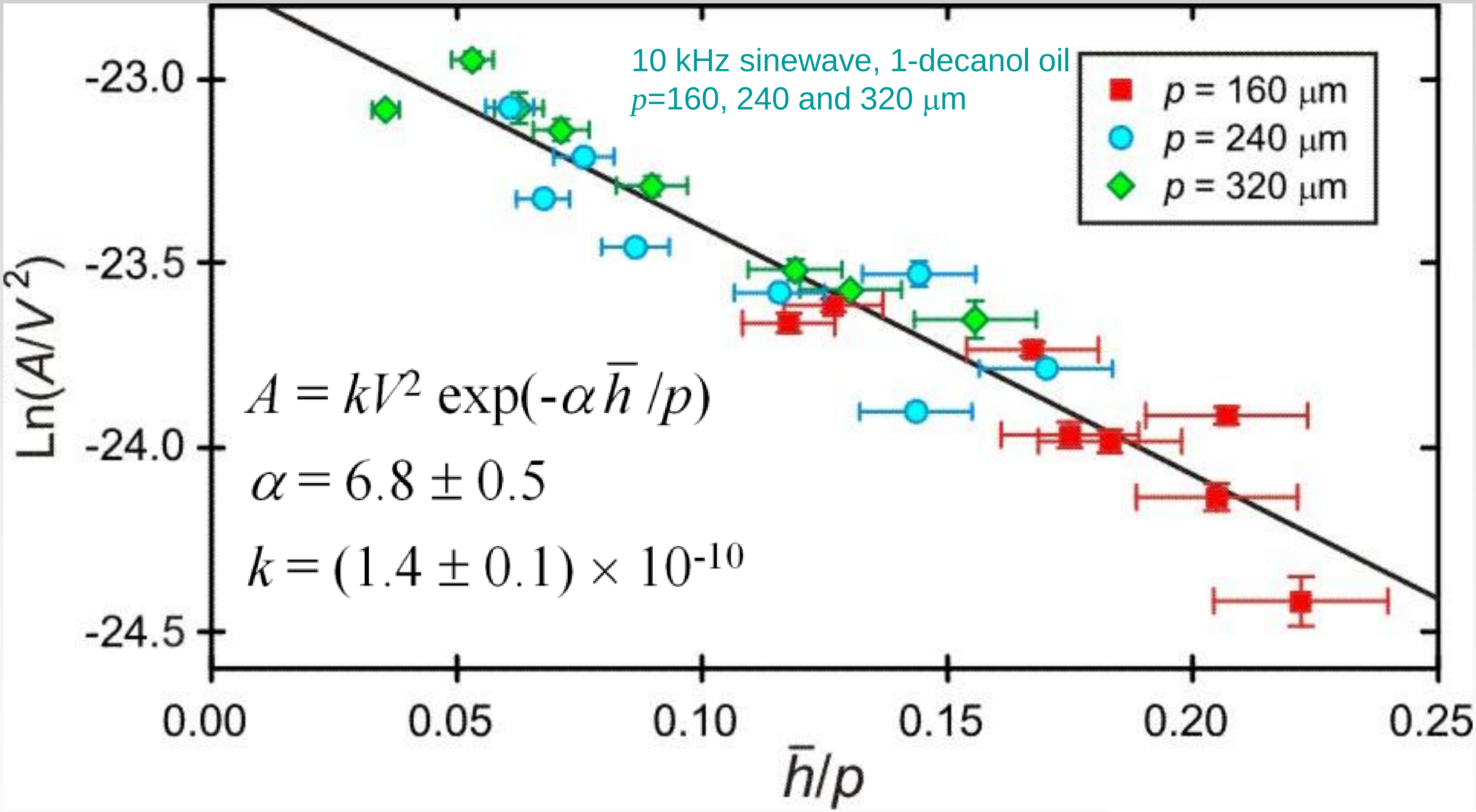
Reference

Brown, C.V. *et al.*, Appl. Phys. Lett.(2010) 97 art. 242904.
McHale, G., *et al.*, Phys. Rev. Lett. (2011) 107 art. 186101.

Statics: Experiments

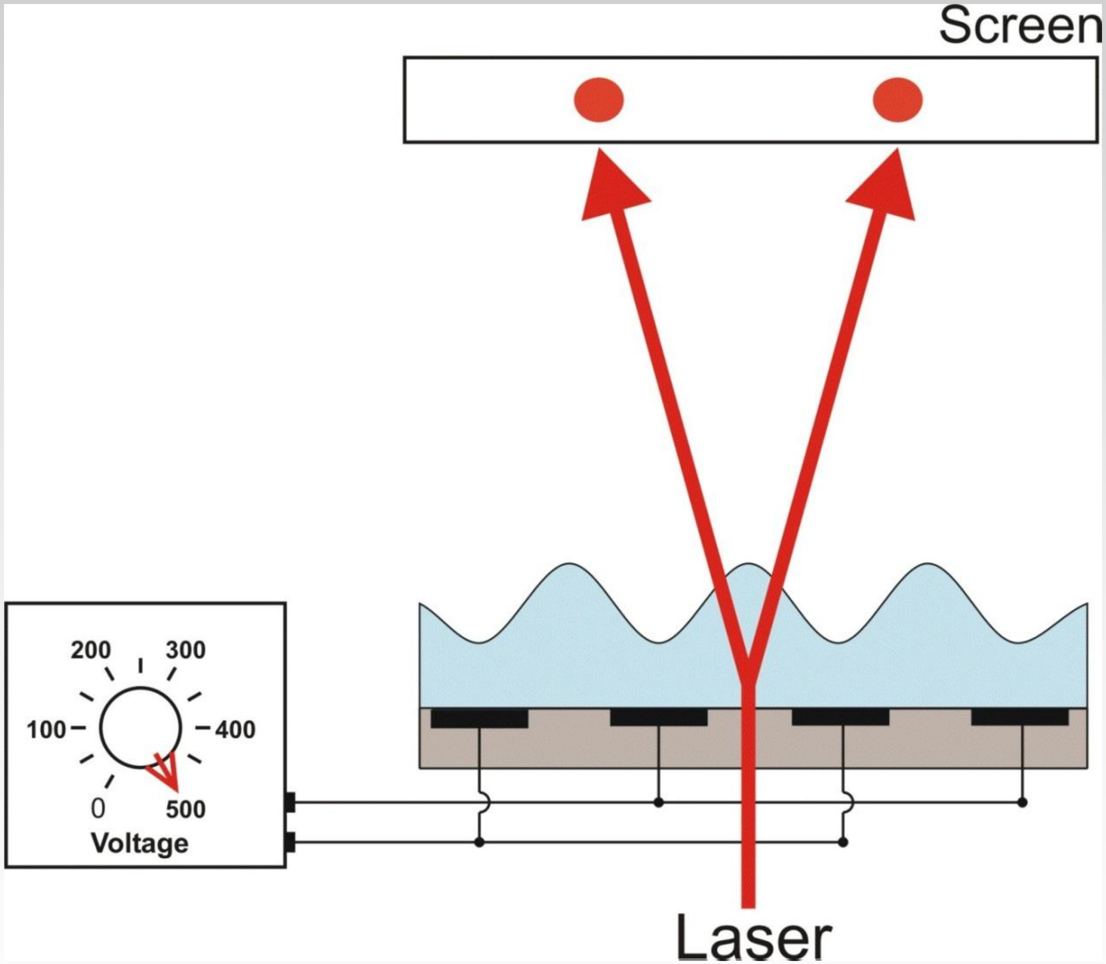
Statics: Experiments

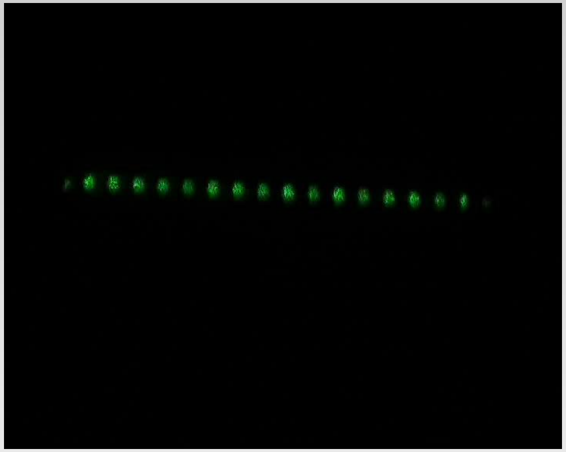
Films: Scaling

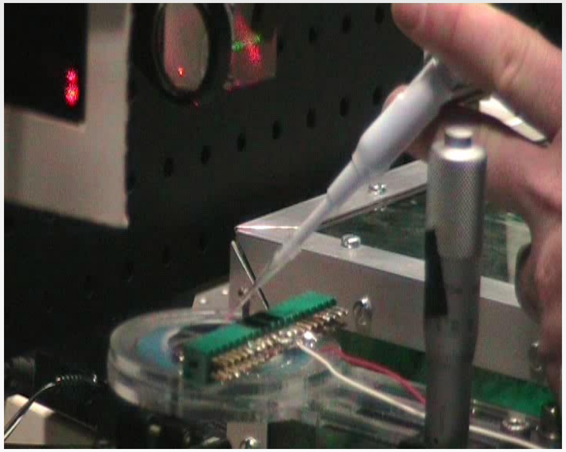


<u>Reference</u> Brown, C.V. *et al.*, Appl. Phys. Lett.(2010) <u>97</u> art. 242904.

Films: Programmable Diffraction



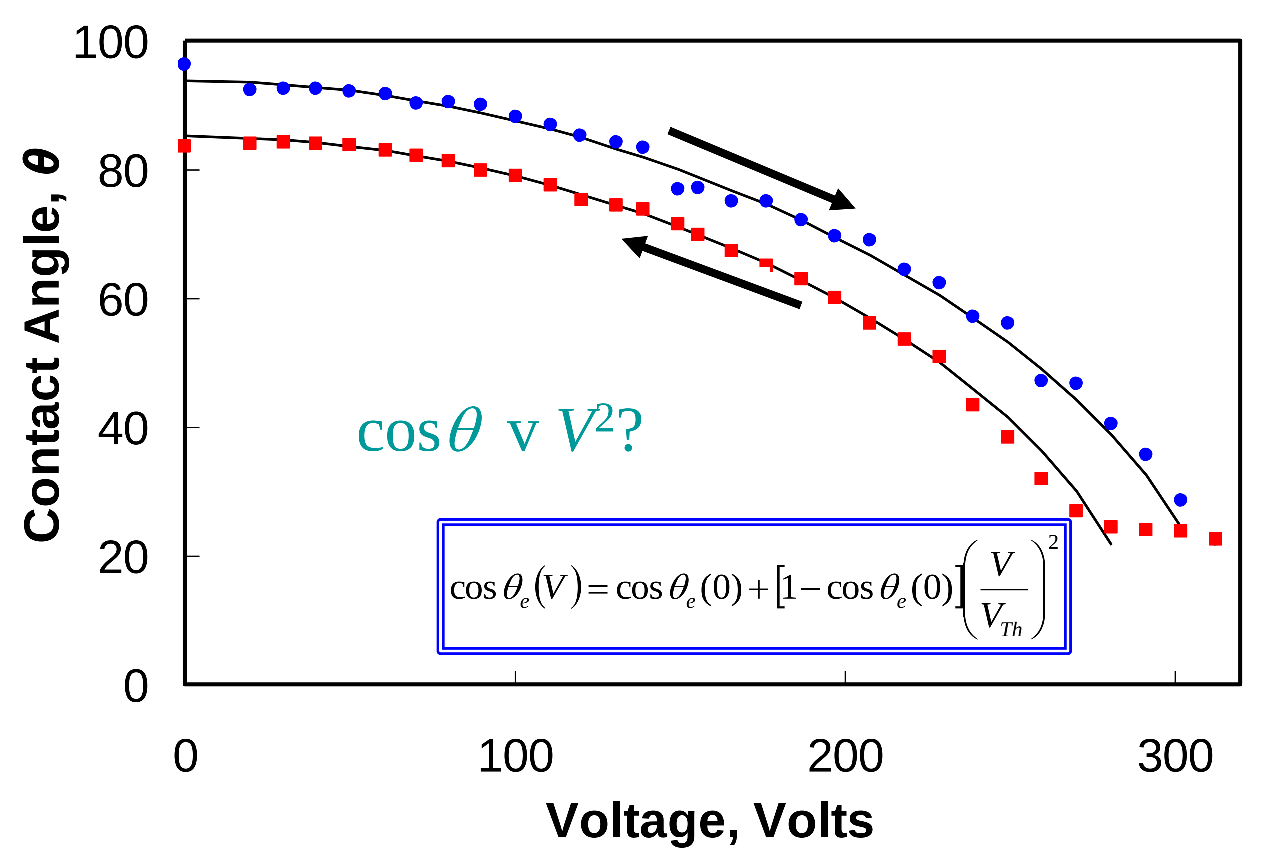




<u>Reference</u> Brown, McHale, *et al*., Nature Photonics (2009) <u>3</u> 403

Stripe Droplet: Dielectrowetting

Experiment - 1,2 polypropylene glycol, electrode pitch 320 μm, 2 μm SU-8 oleophobic capping film, 10 kHz sinewave, monotonic steps to 310 V and back



Side view

Reference McHale, G., *et al.*, Phys. Rev. Lett. (2011) 107 art. 186101.

See PRL for corrections to effective voltage due to thin SU-8 film across electrodes

Dynamics: Theory and Experiment

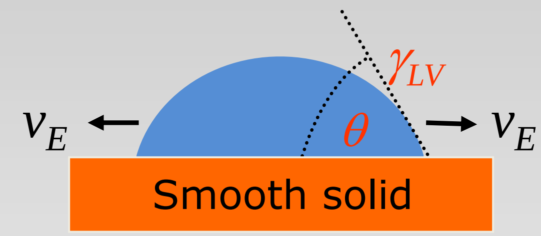
Three Programmable Spreading Regimes

Unbalanced Young's Force

Drop spreads until contact angle $\theta(t)$ reaches equilibrium $\theta_e(V)$

Horizontally projected force $\gamma_{LV}[\cos\theta(t) - \cos\theta_e(V)]$

Viscous dissipation ~ $\eta\, v_E{}^2/\theta(t)$



Modified Hoffman-de Genne's law

$$v_E \approx -k\left(\frac{\gamma_{LV}}{\eta}\right)\theta(t)\left\{\left[\cos\theta(t)-\cos\theta_e(0)\right]-\left[1-\cos\theta_e(0)\right]\left(\frac{V}{V_{Th}}\right)^2\right\}$$

Three Spreading Regimes

Partial Wetting ($V<V_{Th}$)

$$v_E \approx k\left(\frac{\gamma_{LV}}{\eta}\right)\theta_e^2(V)\Delta\theta(t)$$

Exponential approach to equilibrium

Complete Wetting ($V=V_{Th}$)

$$v_E \approx k\left(\frac{\gamma_{LV}}{2\eta}\right)\theta(t)^3$$

Hoffmann or Tanner's Law (for droplets)

Super Wetting ($V>>V_{Th}$)

$$v_E \approx k\left(\frac{\gamma_{LV}}{\eta}\right)\theta(t)\left(1-\cos\theta_e(0)\right)\left(\frac{V}{V_{Th}}\right)^2$$

Voltage induced Superspreading

References

Hoffman, R. L., J. Coll. Interf. Sci. (1975) 50 228. De Gennes, P. G., Rev. Mod. Phys. (1985) 57 827. Tanner, L. H., J. Phys. D: Appl. Phys. (1973) 12 1473. McHale, G., *et al.*, Nature Commun. (2013) 4 art. 1605.

Exponential and Power Law Predictions

Apply to small non-volatile circular arc cross-section stripe and axisymmetric shape spherical cap droplet. Allows closed form solutions for evolution of contact angle and other geometric parameters.

Prediction: There are three regimes in voltage enhanced dynamic wetting and when the liquid is a small non-volatile droplet the contact angle obeys:

$\theta \rightarrow \theta_e$ exponentially with a time constant $\tau(V)$ when $V<V_{Th}$

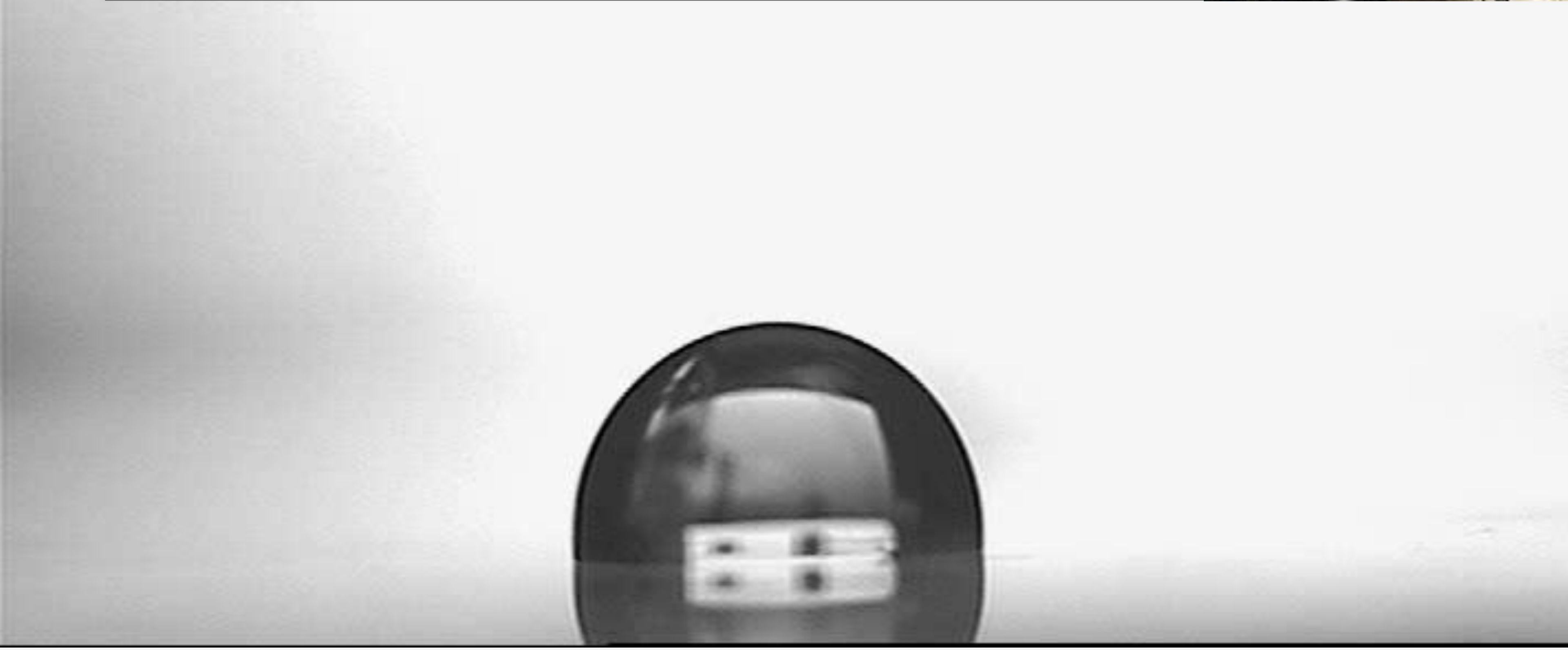
$\theta \propto 1/(t+t_o)^n$ Tanner-type power law when $V \sim V_{Th}$

$\theta \propto 1/(t+t_o)^m$ superspreading power law when $V >> V_{Th}$

	Partial Spreading		Complete Spreading		Super Spreading
Stripes:	$\tau^{-1}(V) \propto k\left(\frac{\gamma_{LV}}{\eta}\right)\theta_e^{7/2}(V)$	$\longrightarrow$	$n=2/7$	$\longrightarrow$	$m=2/3$
Droplets:	$\tau^{-1}(V) \propto k\left(\frac{\gamma_{LV}}{\eta}\right)\theta_e^{10/3}(V)$	$\longrightarrow$	$n=3/10$	$\longrightarrow$	$m=3/4$

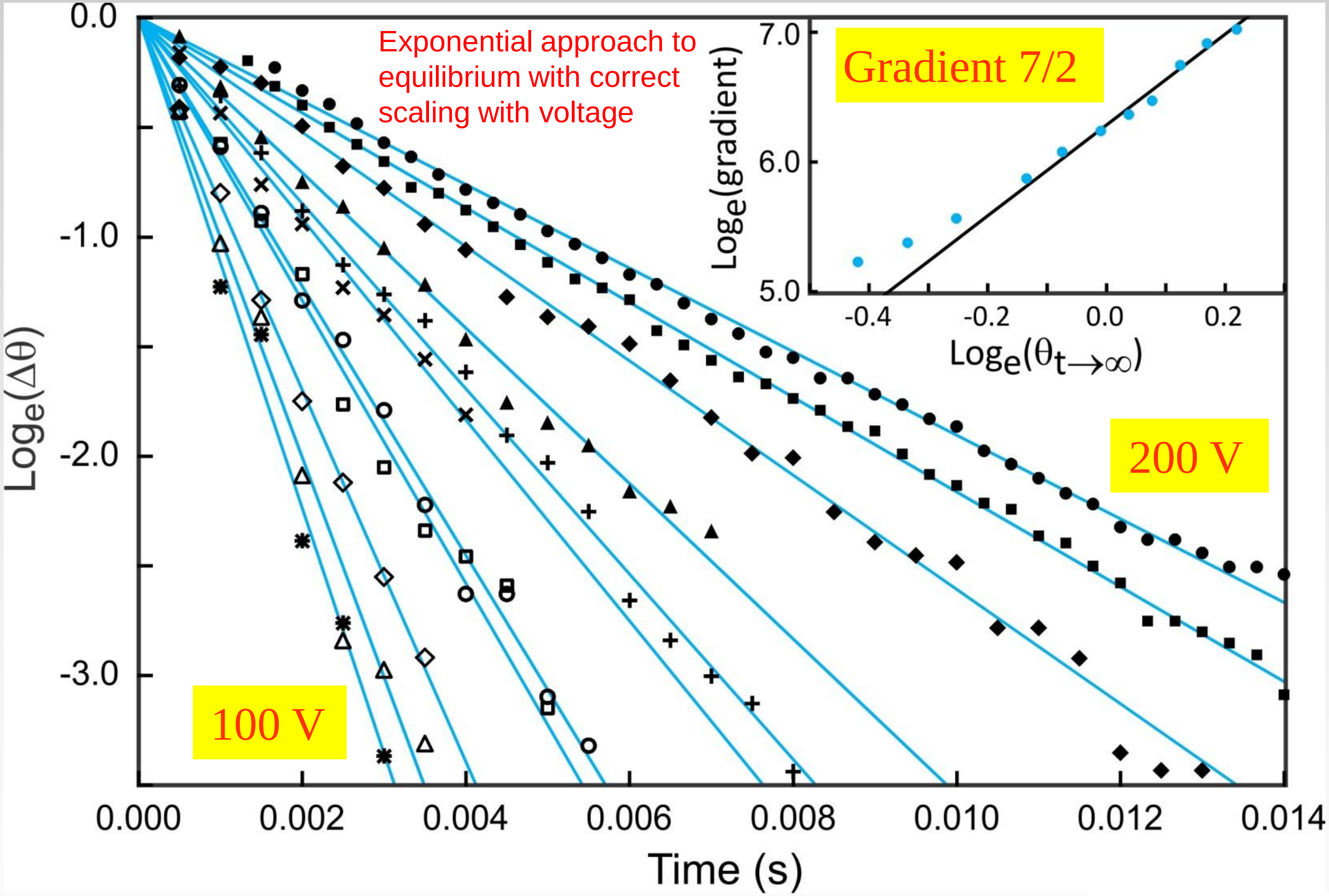
Note: Analogous to topography enhanced superspreading, but roughness is replaced by a tunable voltage (see: McHale, G. *et al.*, J. Phys. D (1995) 28 1925-1929.

Dynamic Contact Angles: Stripe in X-section



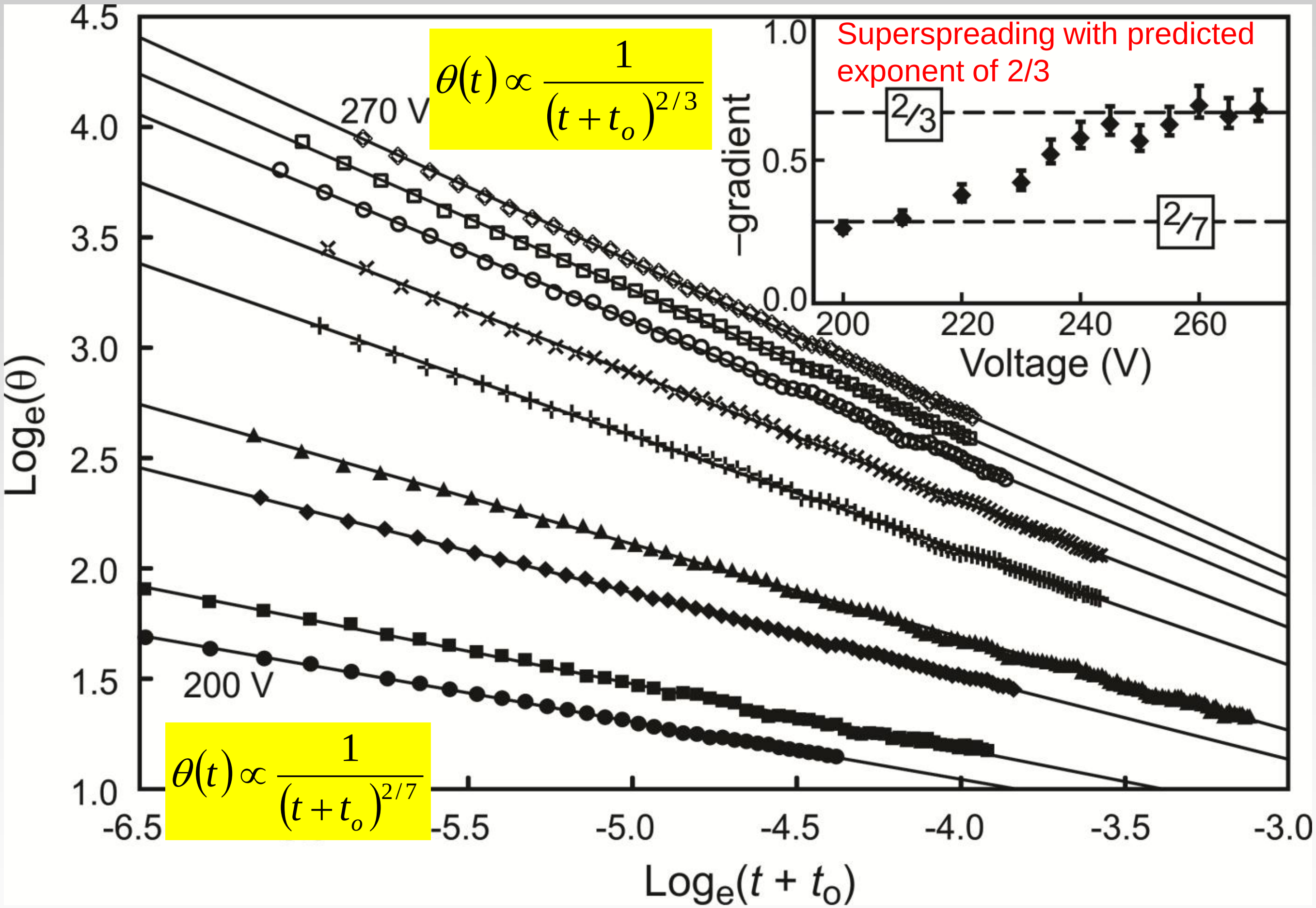
10 kHz sinewave, 1, 2 propylene glycol, electrode pitch p = 160 μm, initial contact angle 95°

Exponential Approach to Equilibrium ($V<V_{Th}$)



<u>Reference</u> McHale, G., *et al.*, Nature Commun. (2013) <u>4</u> art. 1605.

Spreading to Superspreading ($V \geq V_{Th}$)



<u>Reference</u> McHale, G., *et al.*, Nature Commun. (2013) <u>4</u> art. 1605.

Summary and Future Work

Summary

1. Developed theory for L-DEP driven (dielectro-) wetting, i.e. statics
2. Introduced common notational framework to encompass electrowetting
3. Developed theory for voltage driven spreading and superspreading, i.e. dynamics
4. Observed three droplet spreading regimes for stripes including voltage induced super-spreading

Future Work

1. Working on liquid-liquid experiments
2. Axisymmetric droplet shapes
3. Arbitrary shaping of liquid-vapor and liquid-liquid interfaces

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Dr. Gary Wells

The End

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