Dielectrowetting: Statics and Dynamics

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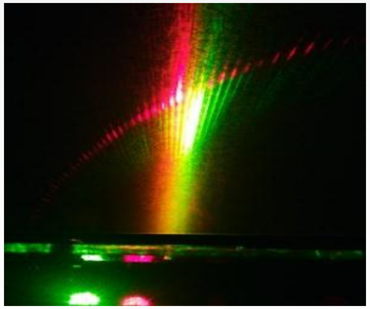


Public Understanding website: http://www.naturesraincoats.com

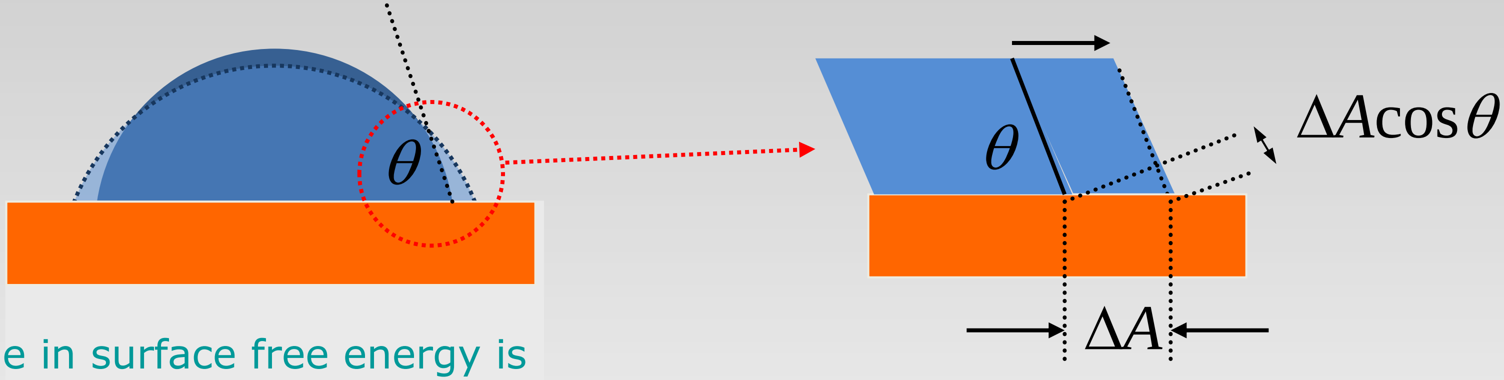
Overview

1. Dielectrowetting: Fundamental Concepts
2. Statics: Droplets and Films (Near and Far Field)
3. Application: Liquid-based Optics
4. Dynamics: Three Droplet Spreading Regimes
5. Dynamics: Edge Speed-Contact Angle Laws
6. Experiments: From Partial to Super-spreading

Dielectrowetting: Fundamental Concepts

Energetics: The Young's Law Equilibrium

What contact angle does a droplet adopt on a flat surface?



Change in surface free energy is

solid-liquid energy per unit area × gain of substrate area - solid-vapor energy per unit area × loss of substrate area + liquid-vapor energy per unit area × gain of liquid-vapor area

$$\Delta F(x)=(\gamma_{SL}-\gamma_{SV})\,\Delta A(x)+\gamma_{LV}\,\Delta A(x)\cos\theta$$

Equilibrium is when $\Delta F(x)=0$ $\Rightarrow$

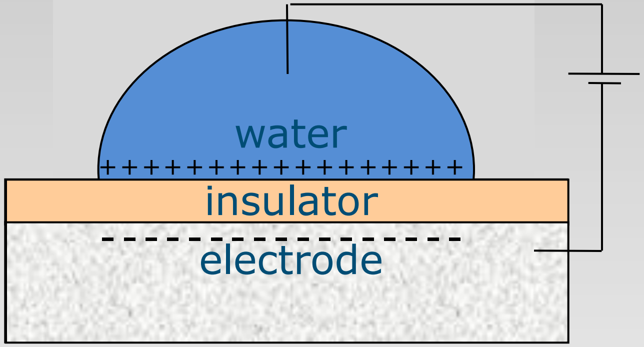
$$\boxed{\cos\theta_e=(\gamma_{SV}-\gamma_{SL})/\gamma_{LV}}$$

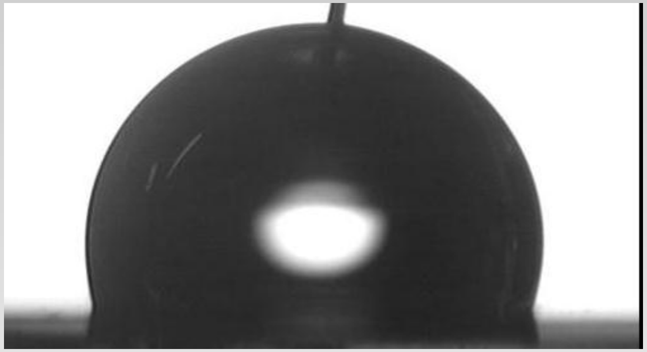
Young's Law

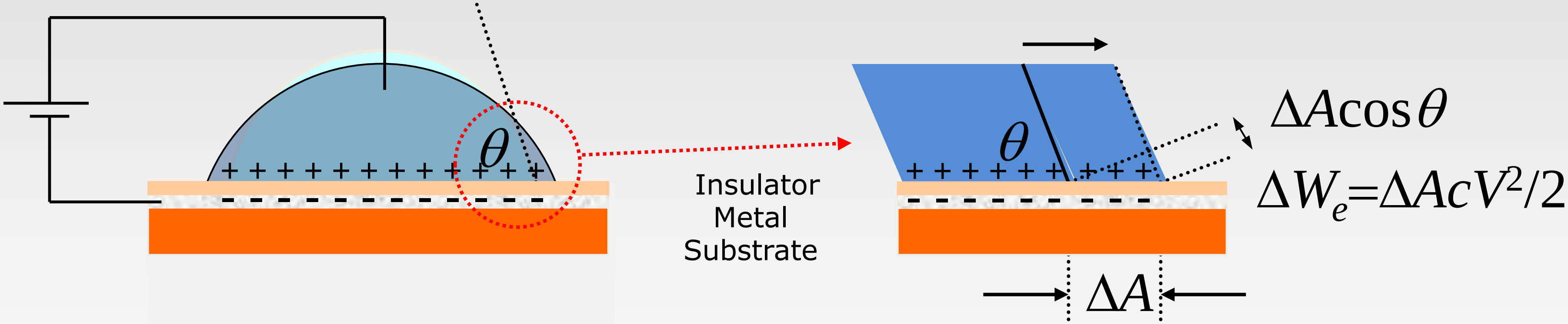
Same result as from resolving forces at contact line

References Shirtcliffe, N.J., *et al.*, An Introduction to Superhydrophobicity, Adv. Colloid Interf. Sci. 161 (2010) 124-138.

Energetics: Electrowetting-on-Dielectric







$\Delta A \cos\theta$

$\Delta W_e = \Delta A c V^2/2$

$\Rightarrow$ $$\boxed{\cos\theta_e(V) = \cos\theta_e(0) + \varepsilon_r\varepsilon_o V^2/2d\gamma_{LV}}$$

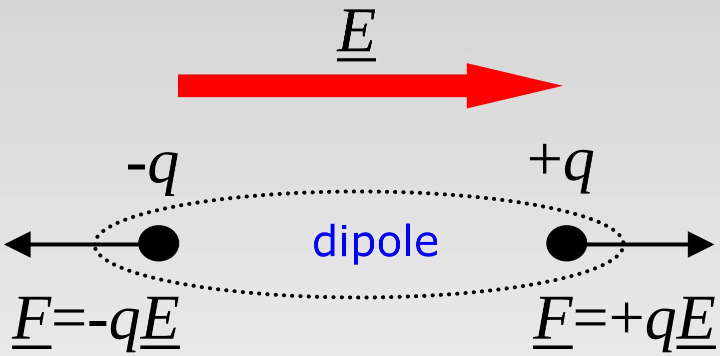
EWOD Modified
Young's Law

References

Berge, B. Comptes Rendus de l' Academie des Sciences Serie II 317 (1983) 157.
Mugele, F. & Baret, J. C., J. Phys.: Condens. Matt. 17 (2005) R705.

Liquid Dielectrophoretic (L-DEP) Forces

Uniform Electric Field Applied



$\underline{E}$

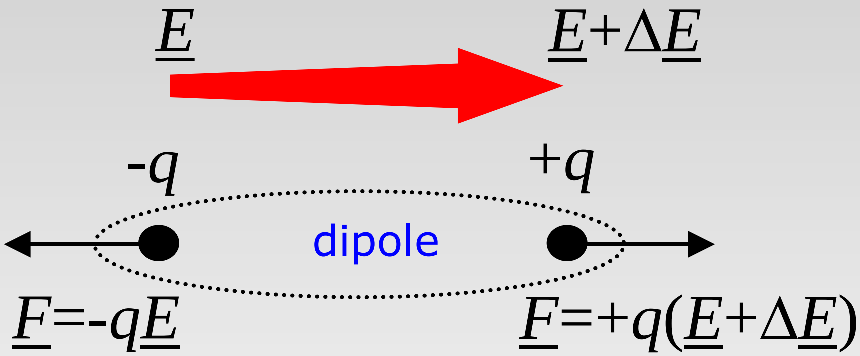
$-q$ $+q$

dipole

$\underline{F}=-q\underline{E}$ $\underline{F}=+q\underline{E}$

Zero net force on dipole

Non-Uniform Electric Field Applied



$\underline{E}$ $\underline{E}+\Delta\underline{E}$

$-q$ $+q$

dipole

$\underline{F}=-q\underline{E}$ $\underline{F}=+q(\underline{E}+\Delta\underline{E})$

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

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

L-DEP Comparison to Electrowetting-on-Dielectric (EWOD)[2]

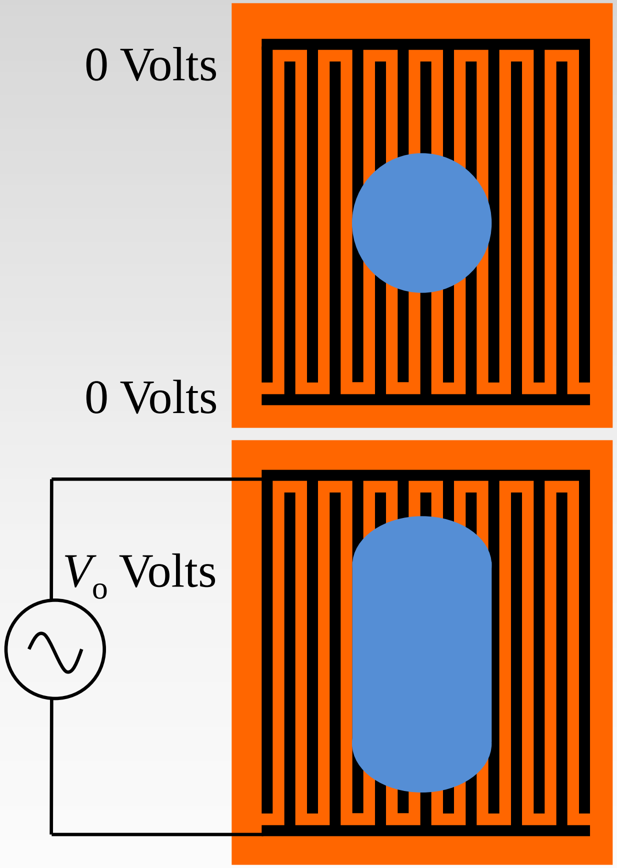
1. L-DEP acts on the bulk material, but EWOD acts at the contact line
2. L-DEP uses dielectric (non-conducting) liquids, but EWOD uses conducting liquids
3. L-DEP does not require electrical contact, but EWOD does require a contact

References 1. Jones, T. B., Langmuir 18, 4437 (2002). Jones, T.B., et al., J. Appl. Phys. 89, 1441 (2001).
2. McHale, G., et al., Phys. Rev. Lett. (2011) 107, art. 186101.

L-DEP Driven Wetting: Three Regimes

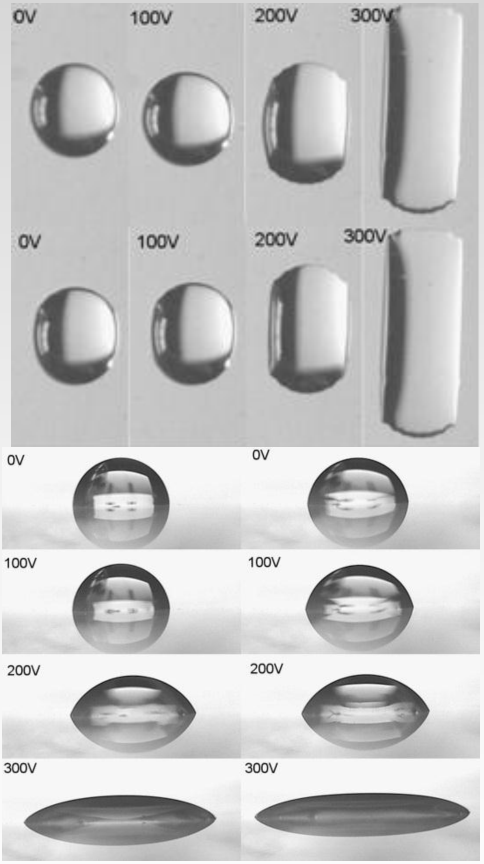
Interdigital Transducers

Top view



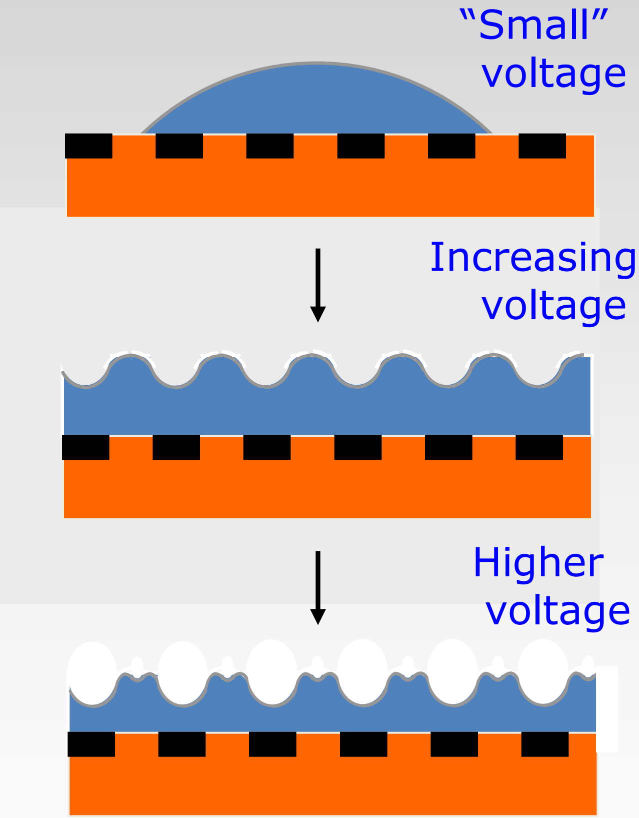
1,2 PPG Droplet

Top and side views*



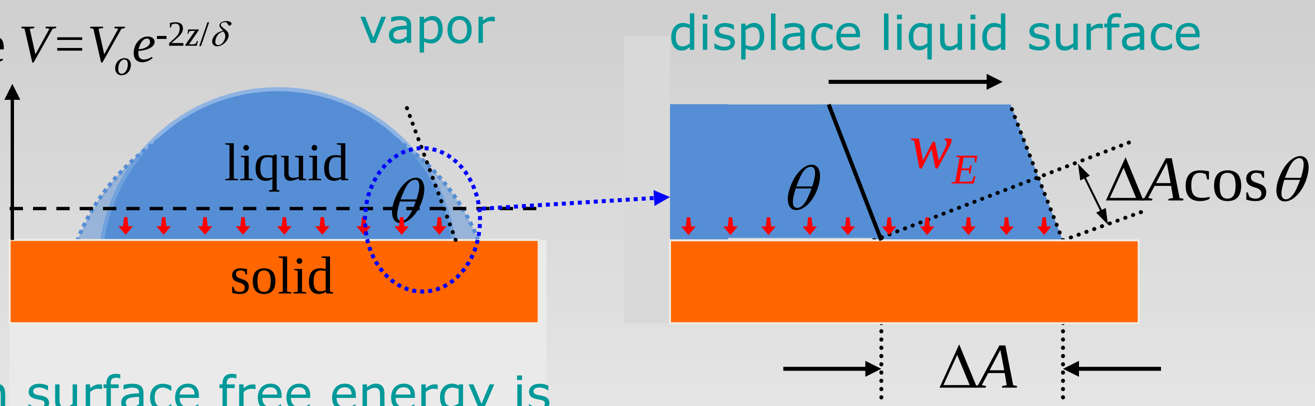
Droplet to Wrinkled Film

Side view



Droplets: Energetics and Dielectrowetting

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



Change in surface free energy is

$$\Delta F=(\gamma_{SL}-\gamma_{SV})\,\Delta A+\gamma_{LV}\,\Delta A\cos\theta-w_E\,\Delta A$$

Exponential field decay into liquid, $E_z=2V_0\exp(-2z/\delta)/\delta \Rightarrow$ pen. depth δ

L-DEP energy is, $w_E\approx\varepsilon_l\varepsilon_o V_o^2\Delta A/2\delta$, assuming a thick droplet

Equilibrium is when $\Delta F=0$

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

L-DEP Modified Young's Law

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

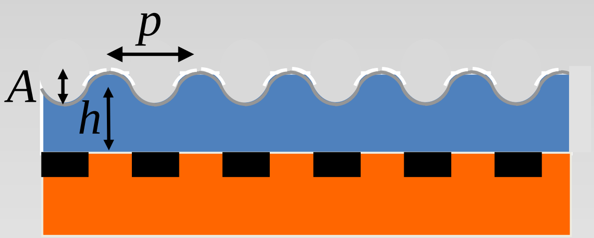
Droplets: DEW versus EWOD

1. DEW is driven by bulk liquid dielectrophoresis, but effective changes localized to contact line changes
2. DEW applies to non-conducting liquids (and conducting liquids at sufficiently high frequencies)
3. DEW is based upon non-uniform electric fields
4. Our DEW implementation uses an in-plane set of interdigitated electrodes and not a sandwich structure with an insulator
5. Our penetration depth, δ, for the non-uniform field is determined by the electrode pitch and this replaces the thickness of insulator, d.
6. Ours is an in-plane format using the ratio of (liquid relative permittivity-1) to penetration depth $(\varepsilon_l-1)\varepsilon_o/\delta$ rather than a sandwich format using ε_s/d

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

Films: Sinusoidal Wrinkles (Far Field)

1. Electric field penetrates to upper liquid-air interface
2. Deformation of liquid-air interface can change surface energy
3. Redistribution of liquid in a pattern following "smoothed" field of IDT alters capacitive energy



Additional surface area: $\Delta A_{LV}=\pi^2A^2/2p$

Decrease in capacitive energy: $\Delta W_{DEP}=\Delta CV(z)^2/2\approx\Delta CV^2\exp(-2\pi h/p)/2$

Capacitance is a function of h/p and scales with $\varepsilon_l\varepsilon_o$, i.e. $C=\varepsilon_l\varepsilon_o f(h/p)$

Change in capacitance is: $\Delta C=(\varepsilon_l\varepsilon_o A/p)[\mathrm{d}f/\mathrm{d}u]_{u=h/p}$

Minimizing energy with respect to changes in amplitude A,

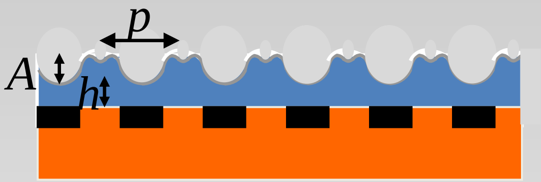
$$\Rightarrow \quad \boxed{A\propto(\varepsilon_l-1)\varepsilon_o V^2\exp(-2\pi h/p)/4\gamma_{LV}}$$

Amplitude Scaling Law*

**Full solution of Maxwell's equation gives same results*

Reference Brown, C.V., *et al.*, Appl. Phys. Lett. 97 (2010) art. 242904; J. Appl. Phys. 110 (2011) art. 024107

Films: Non-Sinusoidal Wrinkles (Near Field)



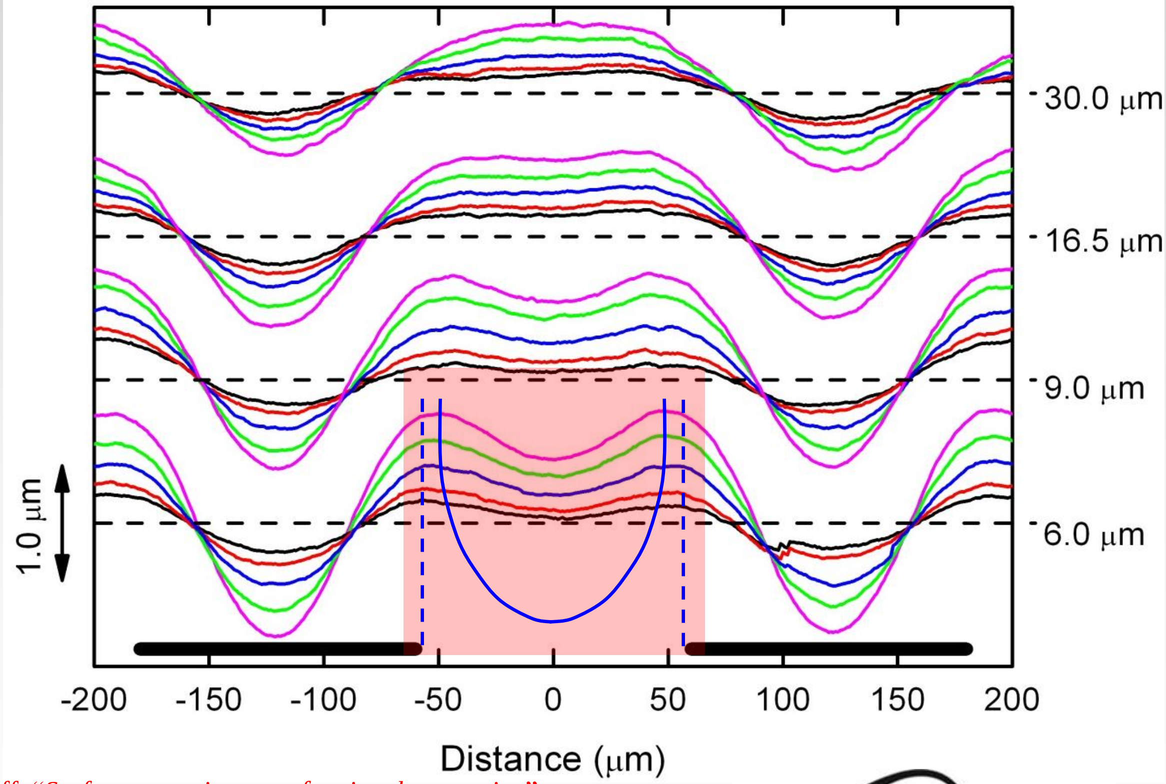
1. Electric field gradients are highest at electrode edges
2. Sinusoid is distorted as it follows IDT edge pattern

Hexadecane

Low dielectric constant
Mach-Zhender interferometer
measured profiles

Voltages ($V_{\text{r.m.s}}$)
275 V (black)
325 V (red)
400 V (blue)
475 V (green)
550 V (magenta)

Dielectric layer
2 µm thick
SU-8



*Electric field sketch after Feldmann and Hénaff, "*Surface acoustic waves for signal processing*"

Reference Brown, C.V., *et al.*, Nature Photonics 3 (2009) 403-405.

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Statics: Droplets and Films

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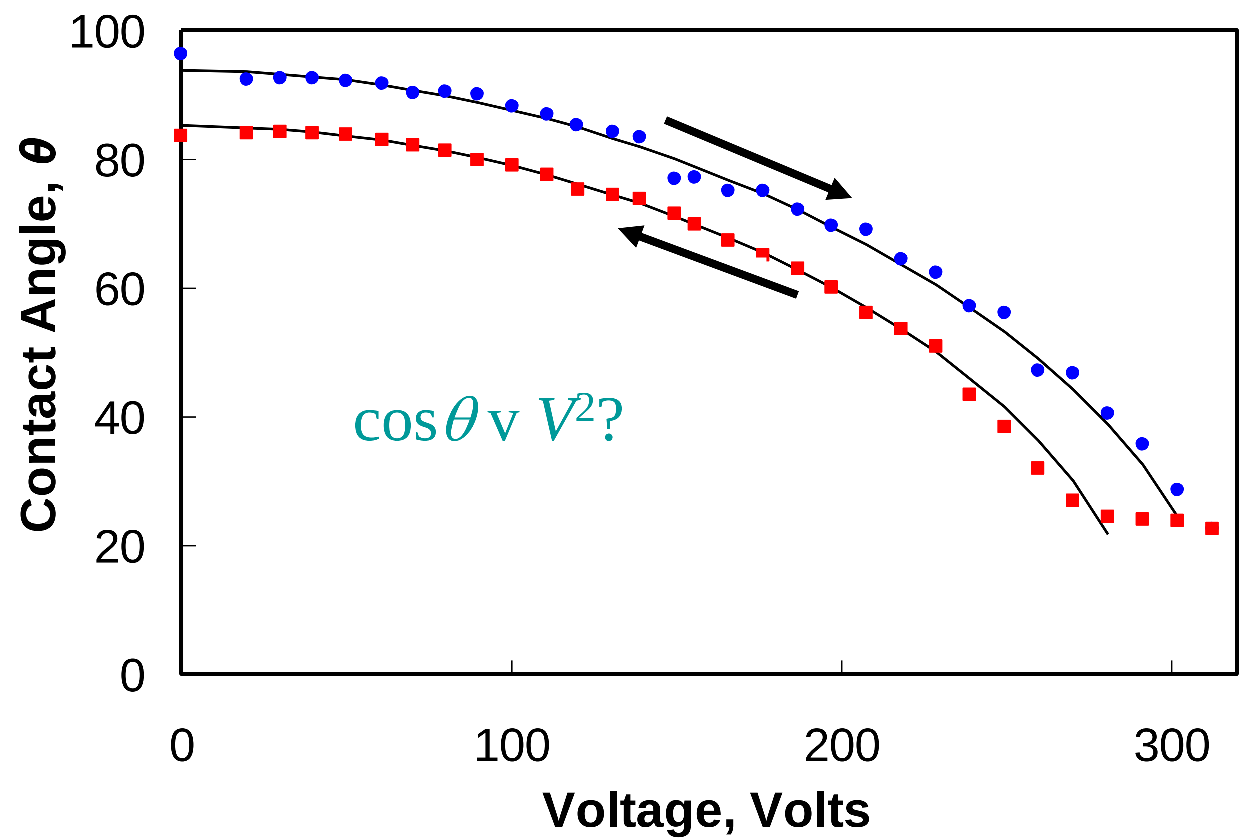
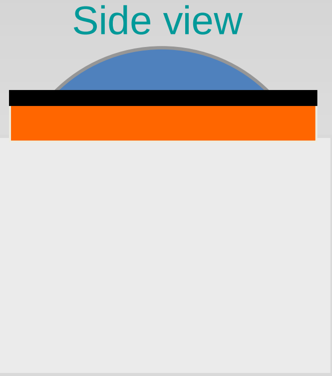
Droplets: Static Contact Angles

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



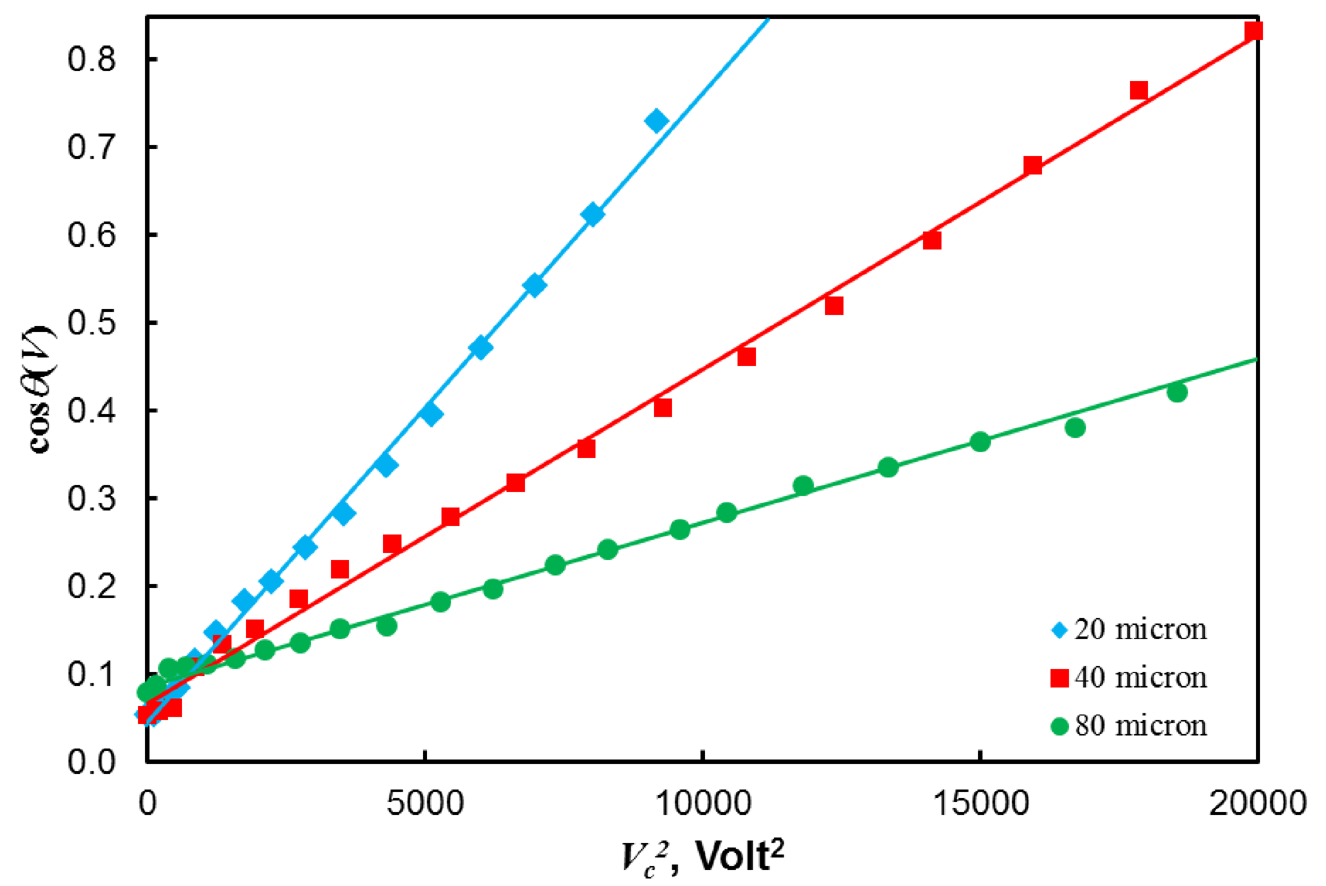
$\cos\theta$ v V^2?



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

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

Droplet Contact Angle: Dependence on Pitch



Electrical pitch $p = 2d$ where d = electrode linewidth = gap between electrodes and $\delta = 2p/\pi$

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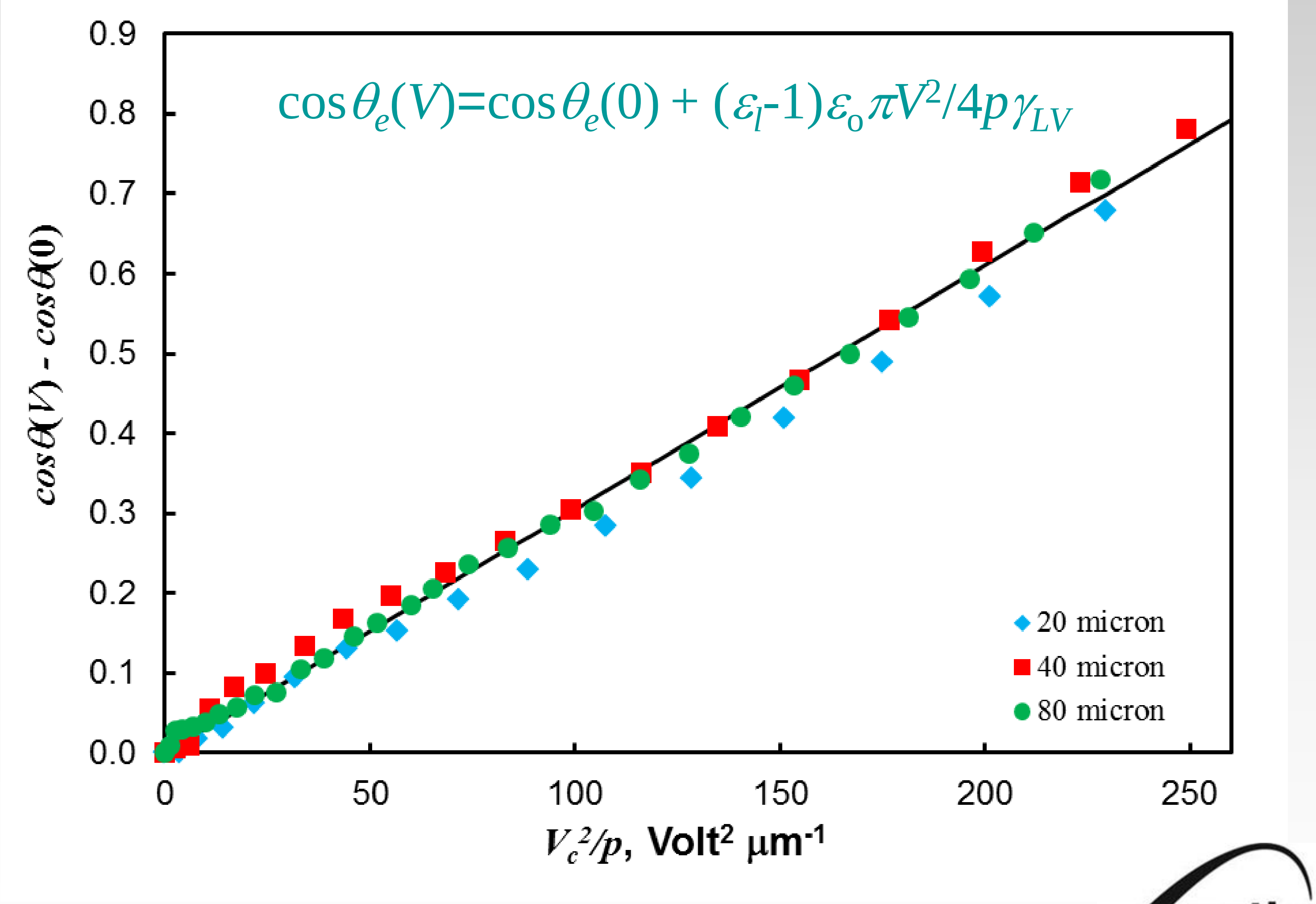
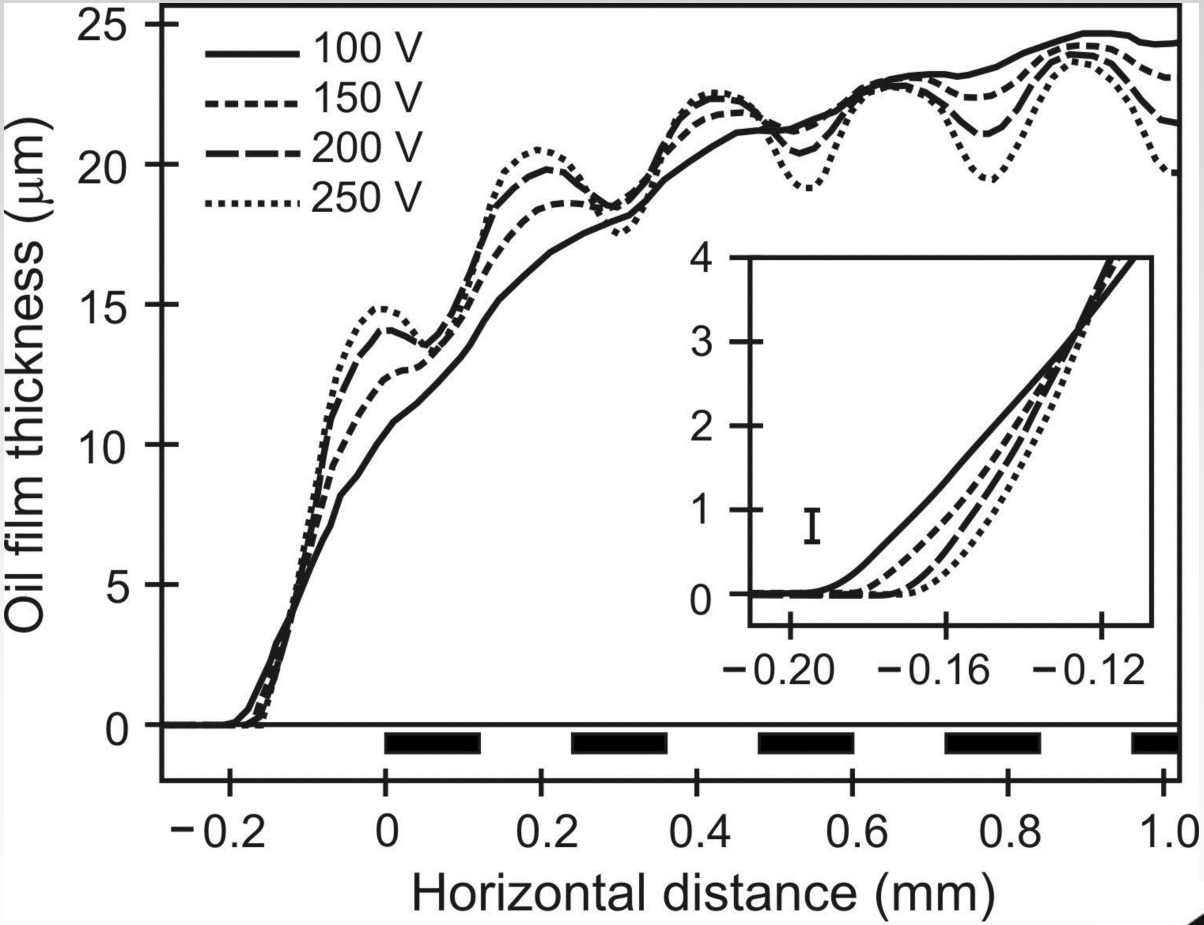
Droplet Contact Angle: Scaling Laws



$$\cos\theta_e(V)=\cos\theta_e(0) + (\varepsilon_l-1)\varepsilon_o\pi V^2/4p\gamma_{LV}$$

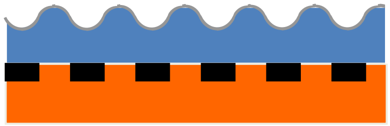
Droplets: Edge Profile

Experiment - Decanol

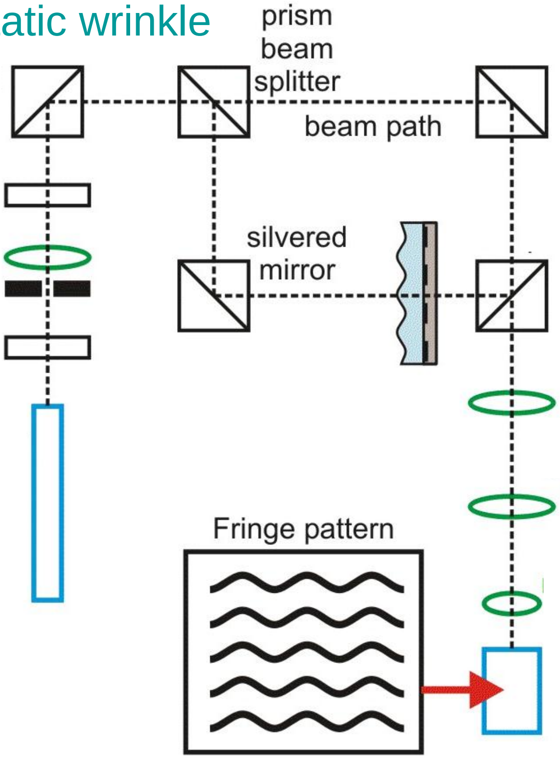


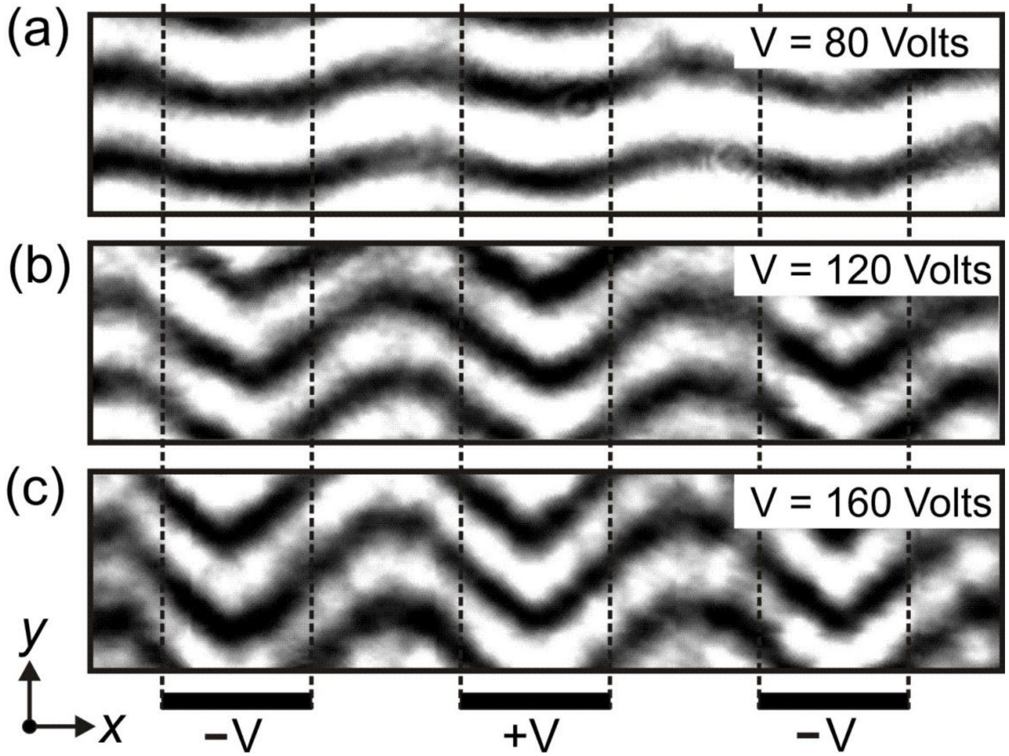
Reference Brown, C.V., *et al*., Appl. Phys. Lett. 97 (2010) art. 242904.

Films (Far-field): Surface Profiles



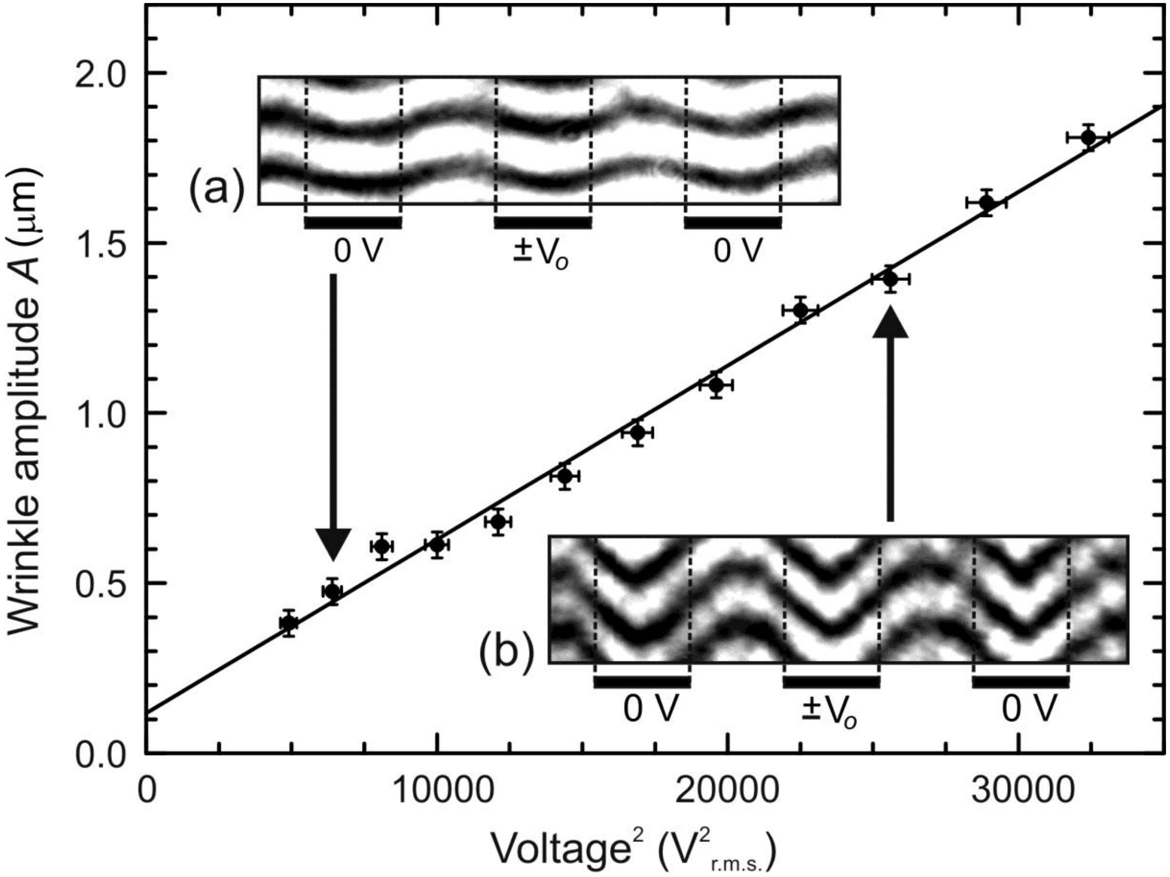
Experiment - Decanol, 10 kHz sinewave, Electrode pitch 320 microns Mach-Zehnder interferometry to visualize static wrinkle





Films (Far-field): Peak-to-Peak Amplitude

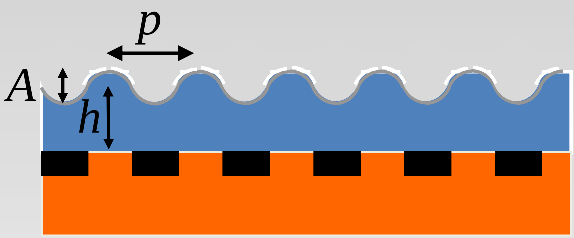
Experiment - Decanol, 10 kHz sinewave, Electrode pitch 320 microns, Mach-Zehnder interferometry to visualize static wrinkle

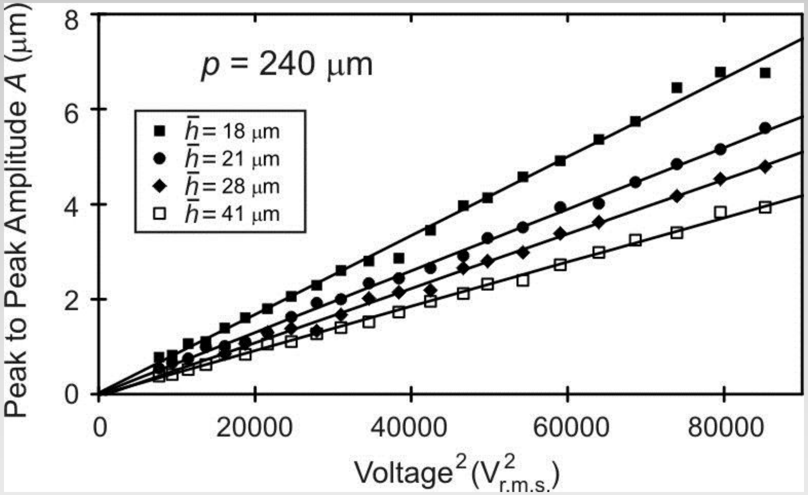


Reference Brown, C.V. *et al*., Nature Photonics 3 (2009) 403-405.

Films (Far-field): Amplitude Scaling Laws

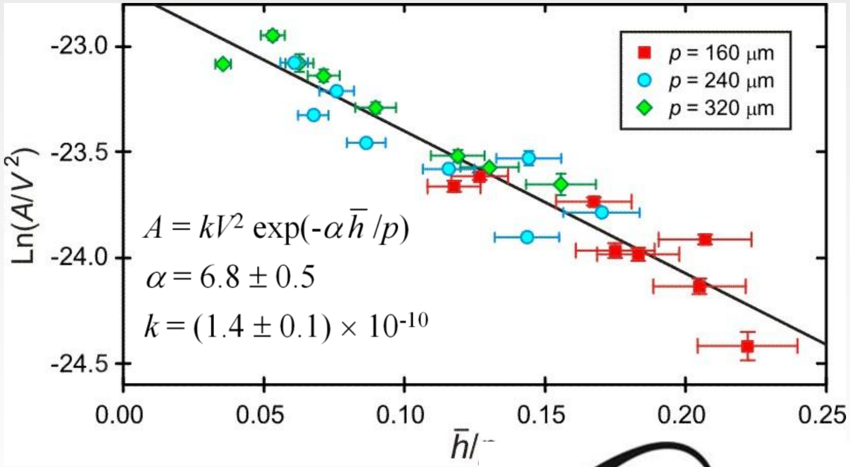
10 kHz sinewave, 1-decanol oil
p=160, 240 and 320 μm





Scaling of amplitude with thickness to electrode periodicity:

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



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

Application: Liquid-based Optics

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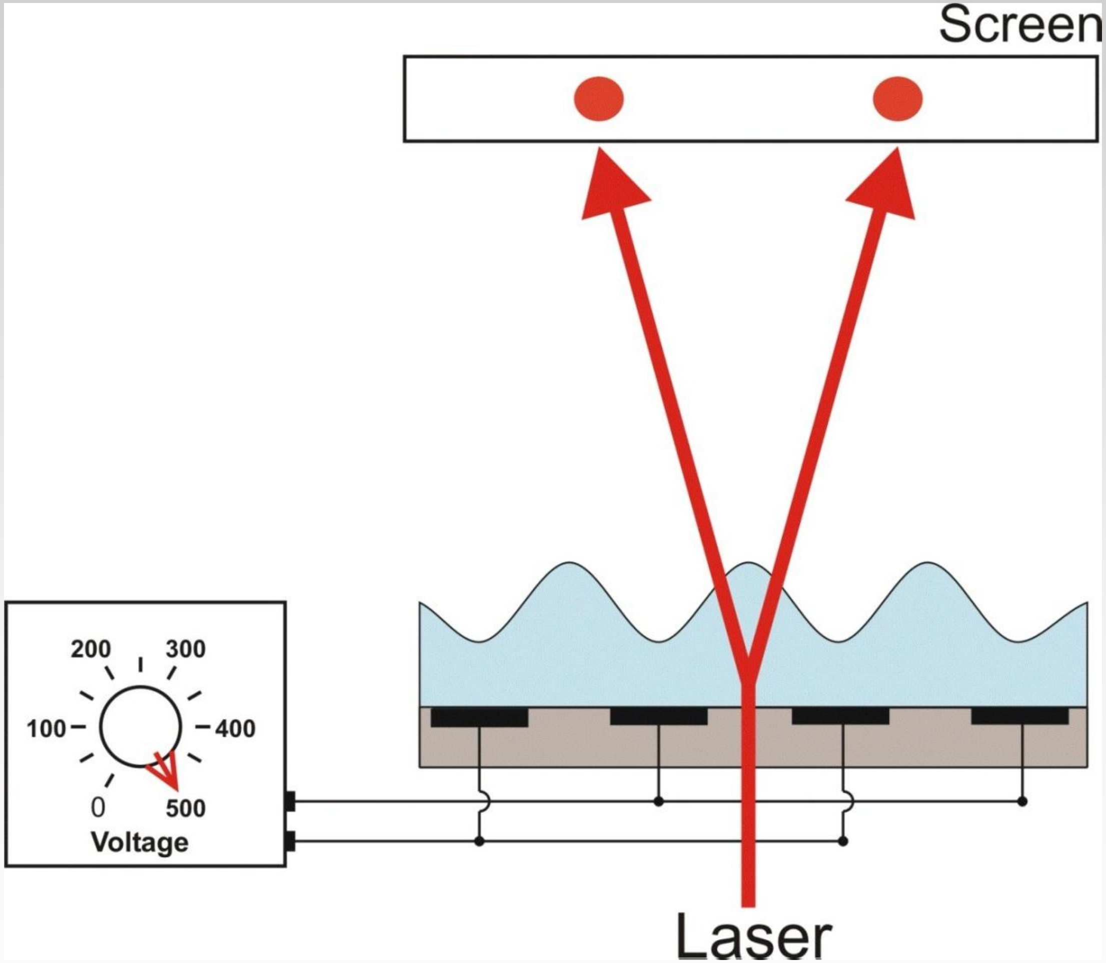
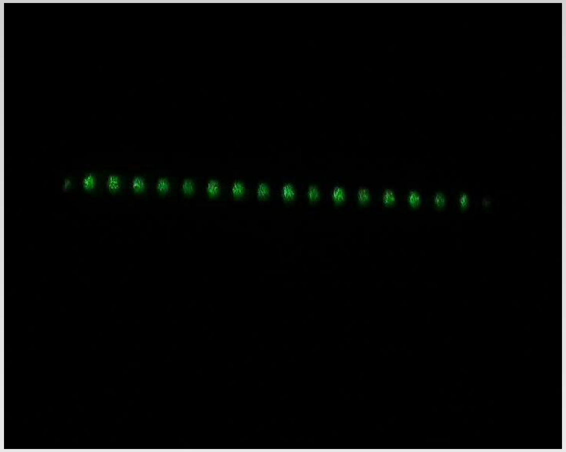
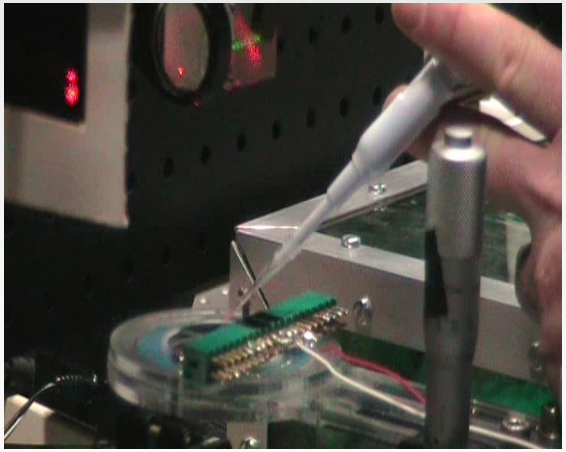
Programmable Phase Grating







Reference Brown, C.V. *et al*., Nature Photonics 3 (2009) 403-405.

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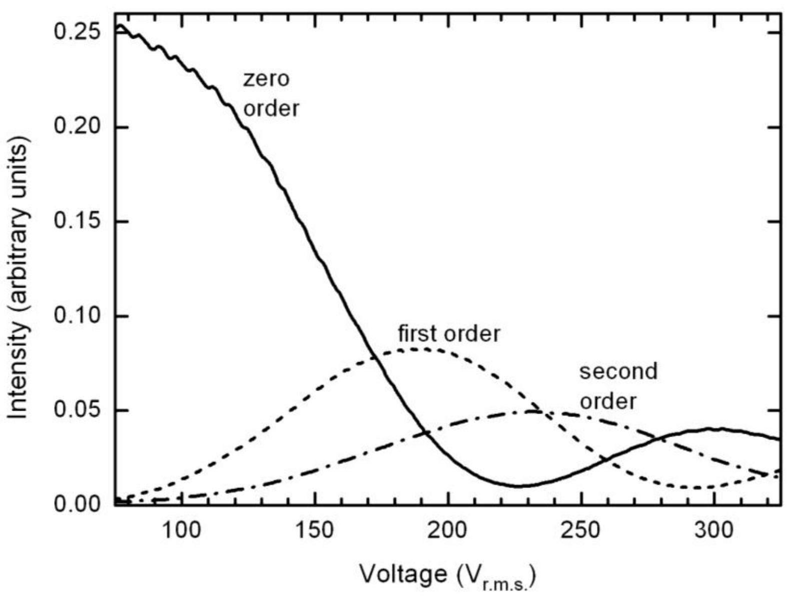
Films: Wrinkle Optics with 1-Decanol Oil

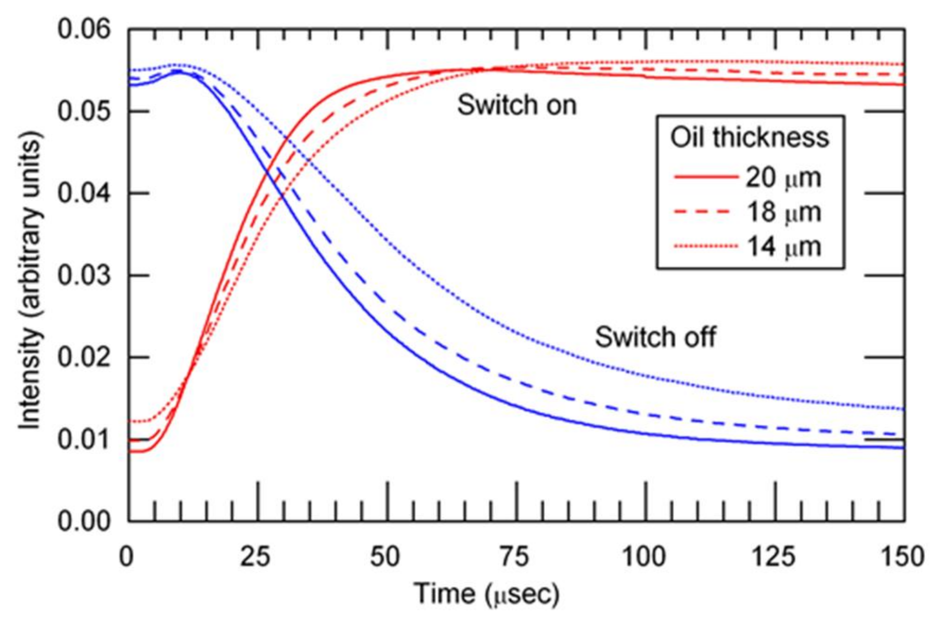
Transmitted Diffracted Orders



zero at 0º, +1 at an angle of 1.56º and +2 at 3.11º

Can tune and set a resin to create solid grating: see Poster 7 and Wells, G.G. *et al.* Optics Letters 36 (2011) 4404-4406.

Switching of First Order



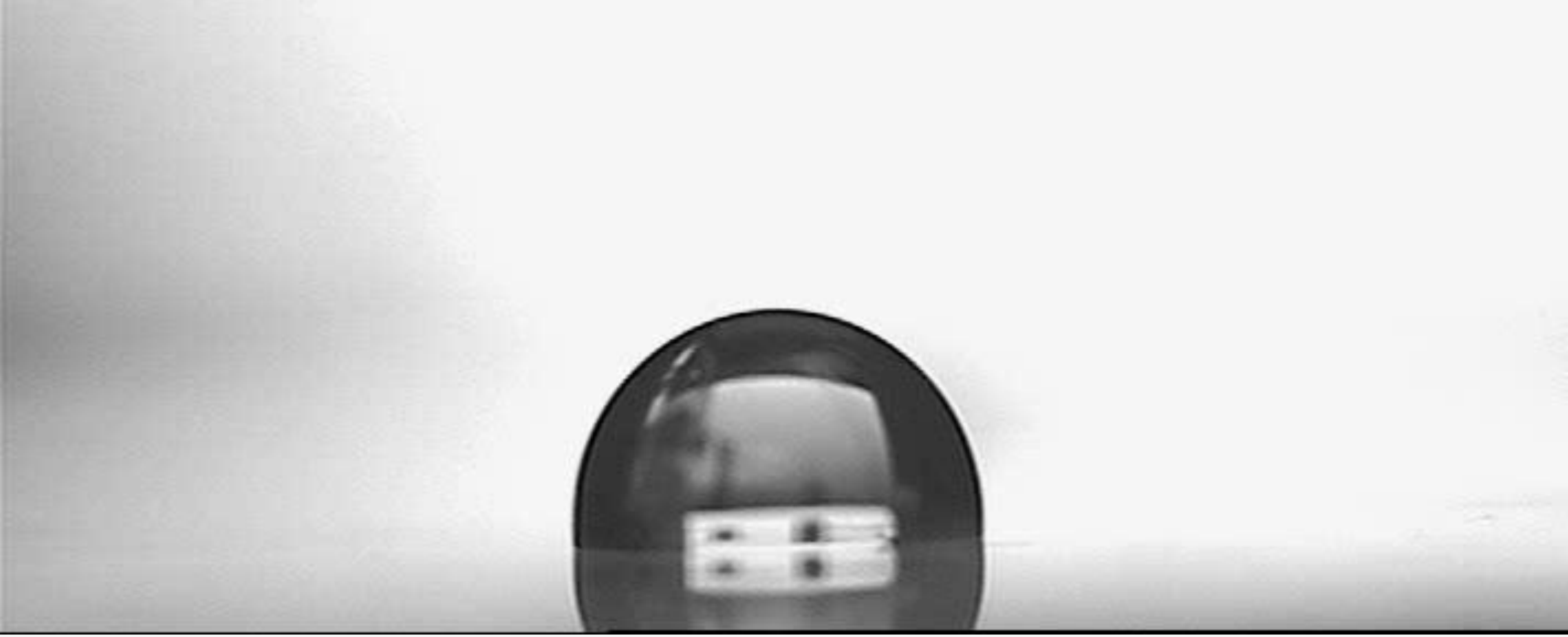
40 μm pitch
Amplitude modulated 10 kHz squarewave
Red line – switch on response within 50 μs
Blue line – switch off response within 100 μs

References: Brown, C.V. *et al*., Nature Photonics 3 (2009) 403-405. Brown, C.V. *et al*., Appl. Phys. Lett. 97 (2010) art. 242904.

Dynamics: Three Droplet Regimes

Dynamics: Three Droplet Spreading Regimes

Dynamic Contact Angles: Stripe in X-section



Isotropic material

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

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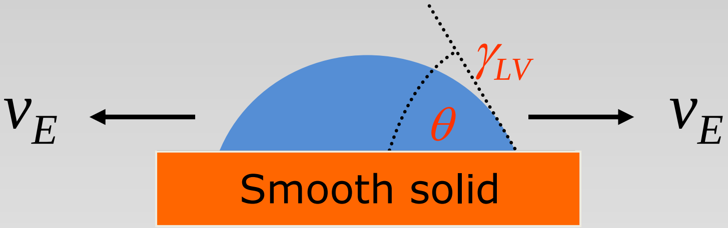
Concept: Driving Forces for Spreading

Drop spreads until contact angle θ reaches
Young's law equilibrium θ_Y

Horizontally projected force $\gamma_{LV}\cos\theta$



Smooth Surface: No Voltage

Driving force ~ $\gamma_{LV}(\cos\theta_Y - \cos\theta)$

Cubic drop edge speed

$$\Rightarrow v_E \propto \theta\,\gamma_{LV}(\theta^2 - \theta_Y^2)$$

Smooth Surface: Voltage

Driving force ~ $\gamma_{LV}(\cos\theta_Y + \beta V^2 - \cos\theta)$

Linear droplet edge speed

$$\Rightarrow v_E \propto \theta\,\gamma_{LV}(\beta V^2+((\theta^2 - \theta_Y^2)/2)$$

Prediction : Voltage (EWOD or Dielectrowetting) modifies edge speed:

$v_E \propto \theta(\theta^2 - \theta_Y^2)$ changes towards $v_E \propto \theta$

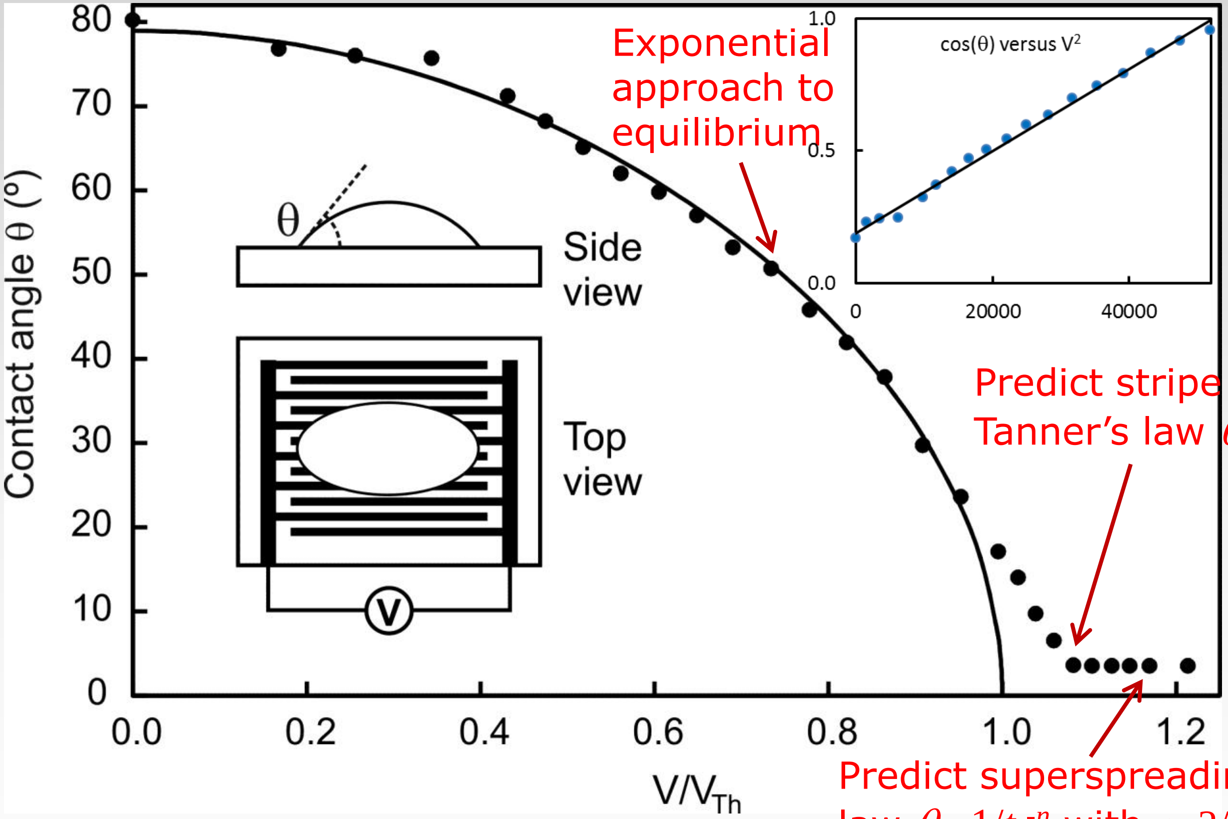
In extreme limit, similar effect on dynamics as topography induced superspreading*

Reference McHale, G.; Newton, M.I. Colloids & Surfaces, A206 (2002) 193-201.

*McHale, G., *et al*., Phys. Rev. Lett. 93 (2004) art. 036102.

Predictions: Partial Wetting to Superspreading

Stripe geometry, 160 μm pitch, 1,2 PPG @ 10 kHz, conserved volume, voltage reset between each measurement, deduced threshold V_{Th}=229 V (or slightly less)



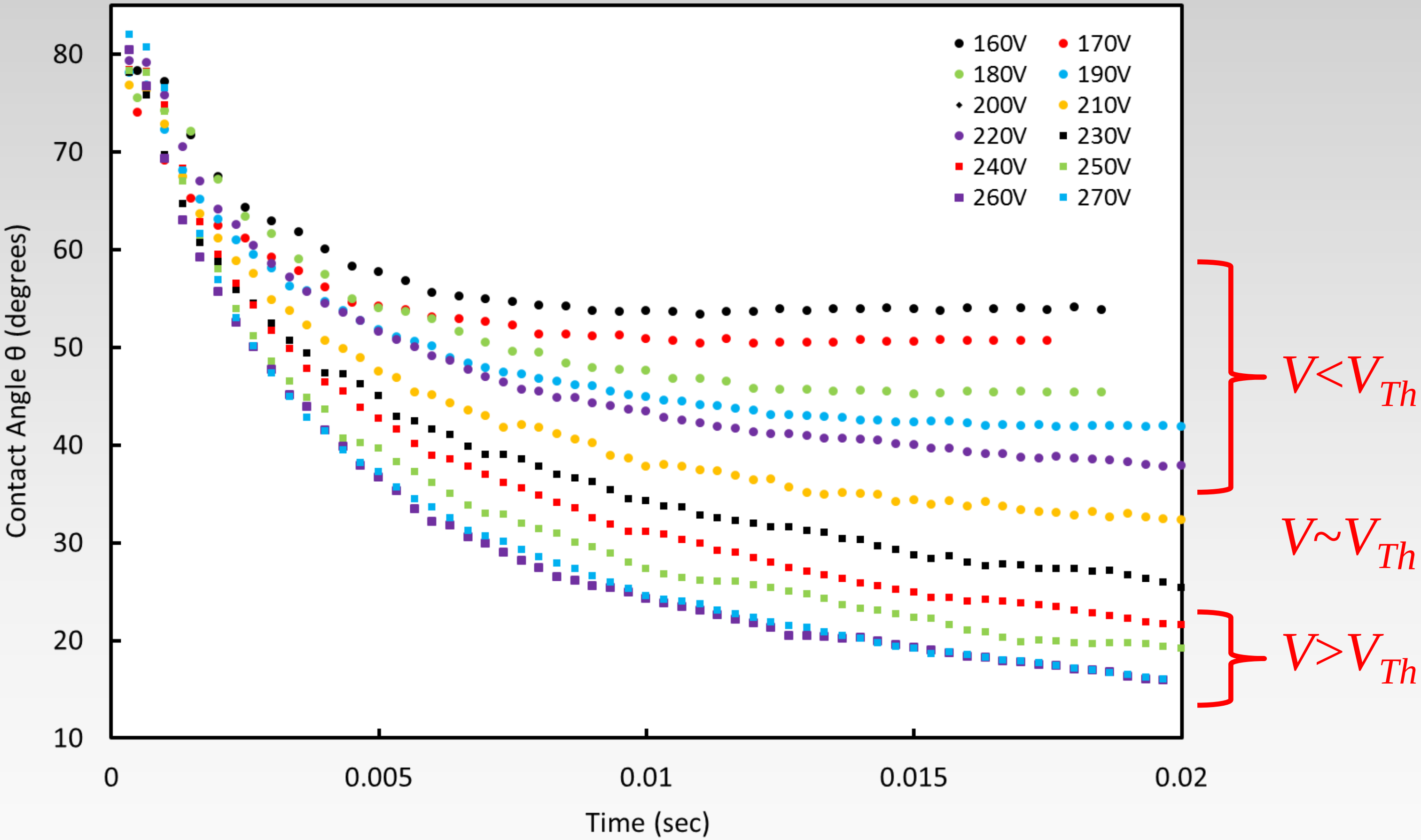
Exponential approach to equilibrium

Predict stripe version* of Tanner's law $\theta \sim 1/t^{n}$ with $n=2/7$

Predict superspreading law $\theta \sim 1/t^{-n}$ with $n=2/3$

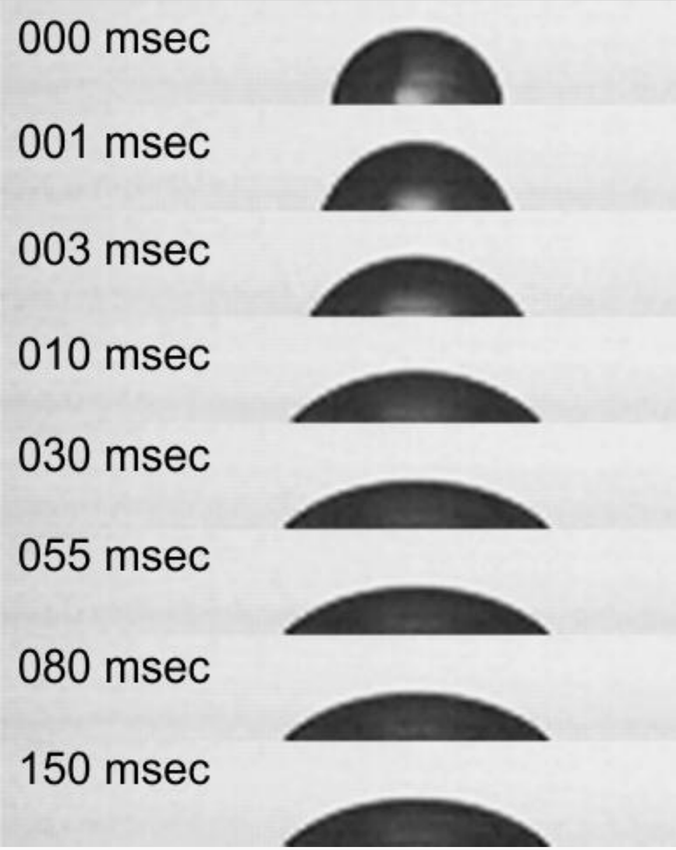
*Stripe version of Tanner's Law: McHale, G. *et al.*, J. Phys. D 28 (1995) 1925-1929

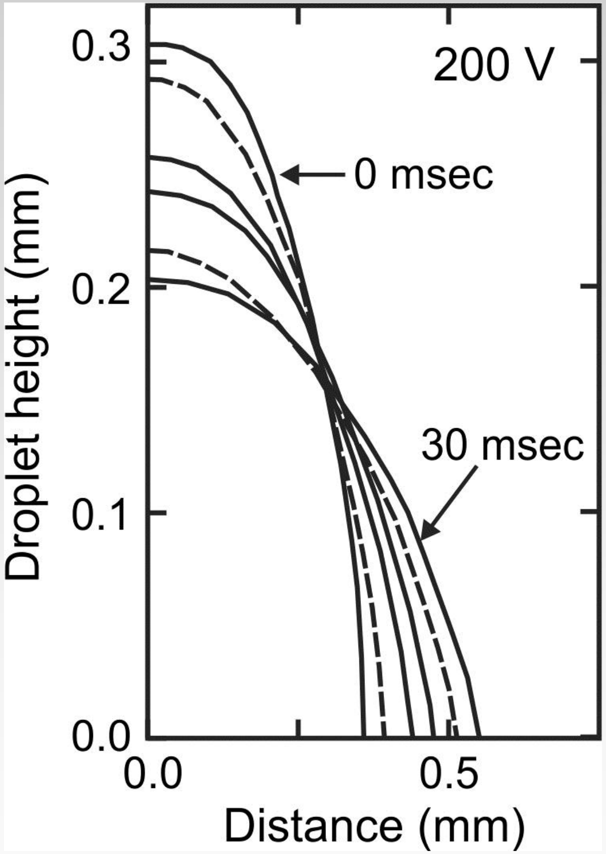
Observations: Stripe Dynamic Contact Angle



10 kHz sinewave, 1, 2 propylene glycol ,electrode pitch *p* = 160 μm,
Initial contact angle 78°

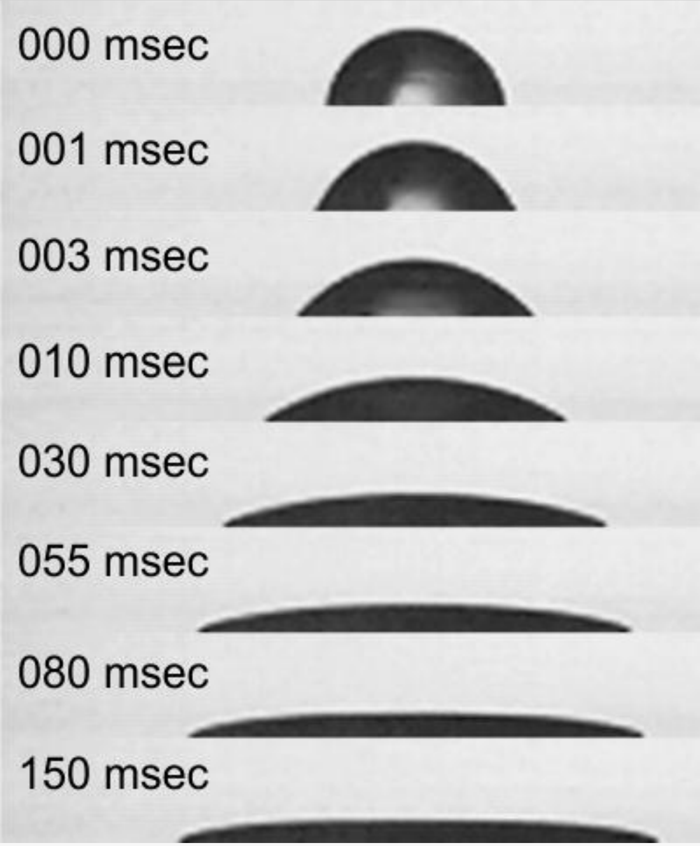
Profile Evolution: Partial Wetting $(V<V_{Th})$

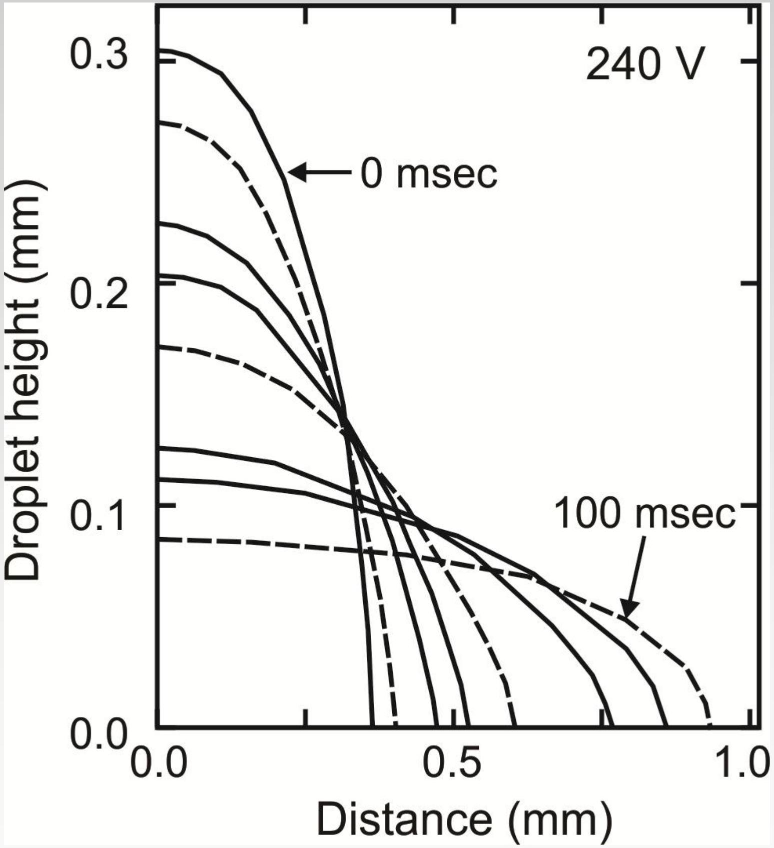




10 kHz sinewave, 1, 2 propylene glycol ,electrode pitch p = 160 μm,
Initial contact angle 78°

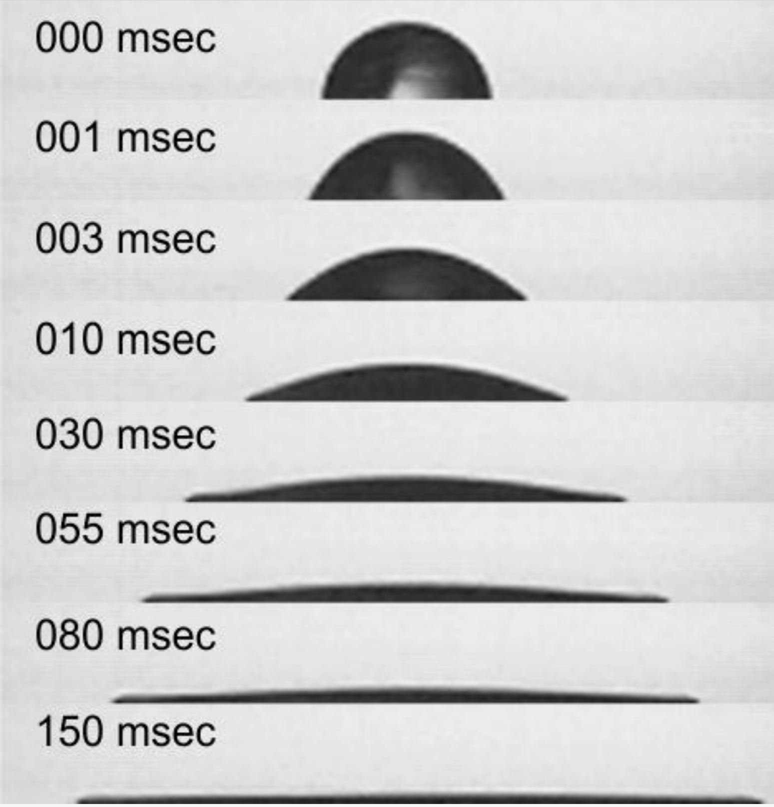
Profile Evolution: Complete Wetting $(V \sim V_{Th})$

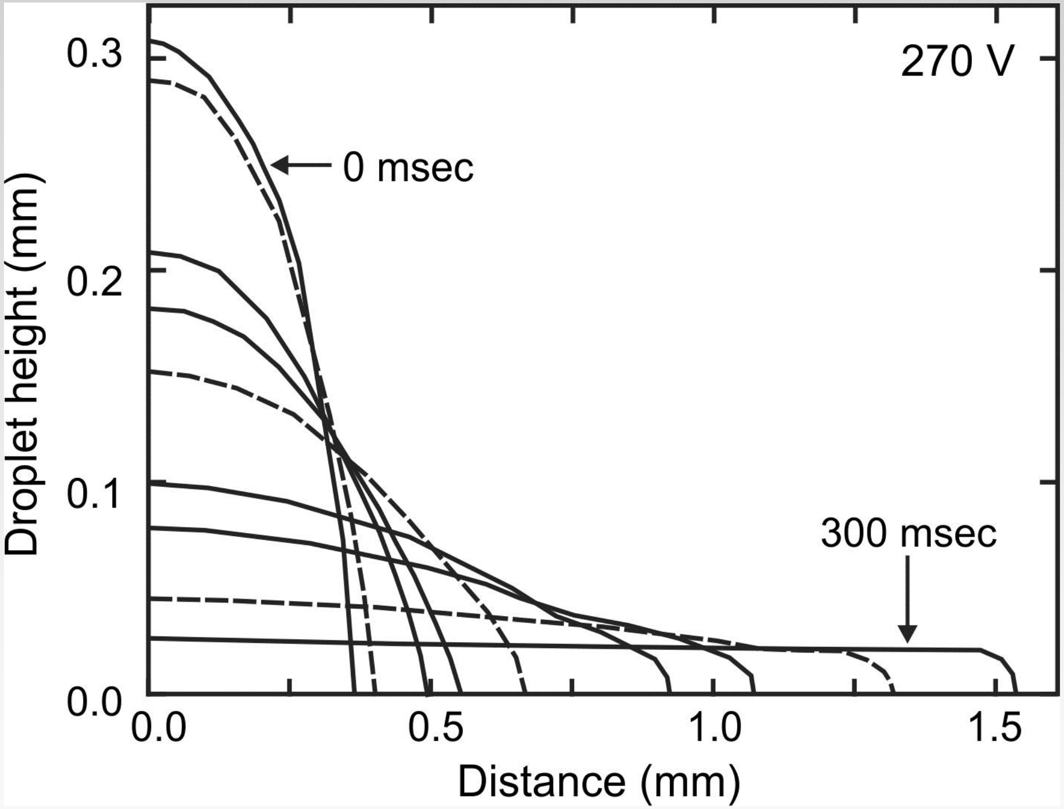




10 kHz sinewave, 1, 2 propylene glycol ,electrode pitch p = 160 μm,
Initial contact angle 78°

Profile Evolution: Superspreading ($V>V_{Th}$)





10 kHz sinewave, 1, 2 propylene glycol ,electrode pitch p = 160 μm,
Initial contact angle 78°

Dynamics: Edge Speed-Contact Angle Law

Dynamics: Edge Speed-Contact Angle Law

Voltage Modified Hoffmann-De Gennes Law

Effect of voltage on contact angle for both electrowetting and dielectrowetting can be summarized using the threshold voltage, V_T, to complete wetting, i.e. $\theta_e(V_T)=0$,

$$\cos\theta_e(V) = \cos\theta_Y - [\cos\theta_Y - 1]\left(\frac{V}{V_{Th}}\right)^2$$

The Hoffman-de Genne's law relating the dynamic contact angle, θ, to edge speed, v_E, is modified to:

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

Three regimes occur:

Partial Wetting	Complete Wetting	Super Wetting
$v_E \approx k\left(\frac{\gamma_{LV}}{\eta}\right)\theta_e^2(V)\Delta\theta(t)$	$v_E \approx k\left(\frac{\gamma_{LV}}{2\eta}\right)\theta(t)^3$	$v_E \approx k\left(\frac{\gamma_{LV}}{\eta}\right)\theta(t)(1-\cos\theta_Y)\left(\frac{V}{V_{Th}}\right)^2$
Exponential approach to equilibium	Hoffmann or Tanner's Law (for droplets)	Voltage induced Superspreading

References

Hoffman, R. L., J. Colloid Interf. Sci. 50 (1975) 228-241. De Gennes, P. G., Rev. Mod. Phys. 57 (1985) 827-863. Tanner, L. H., J. Phys. D: Appl. Phys. 12 (1979) 1473-1484. McHale, G. ; Brown, C.V. & Sampara, N., In preparation.

Exponential and Power Laws: Drop Shapes

Can apply this to spreading of a small non-volatile circular arc cross-section stripe or an axisymmetric shape spherical cap droplet. Allows closed form solutions for evolution of contact angle and other geometric parameters to be found.

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 $V >> V_{Th}$

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:

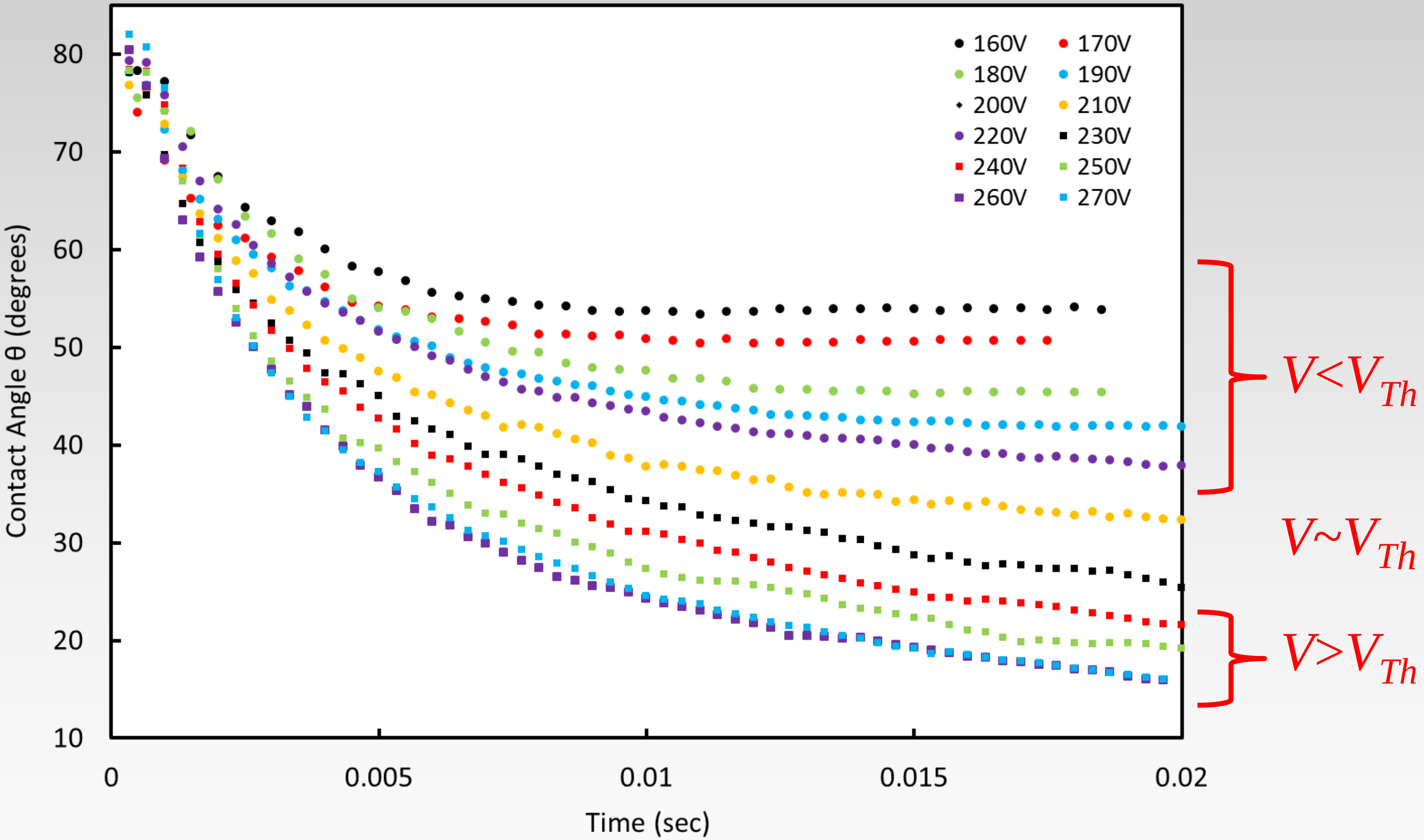
$$\tau^{-1}(V) \propto k\left(\frac{\gamma_{LV}}{\eta}\right)\theta_e^{10/3}(V) \longrightarrow n=3/10 \longrightarrow m=3/4$$

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

Experiments: Partial to Super-spreading

Experiments: Partial to Super-spreading

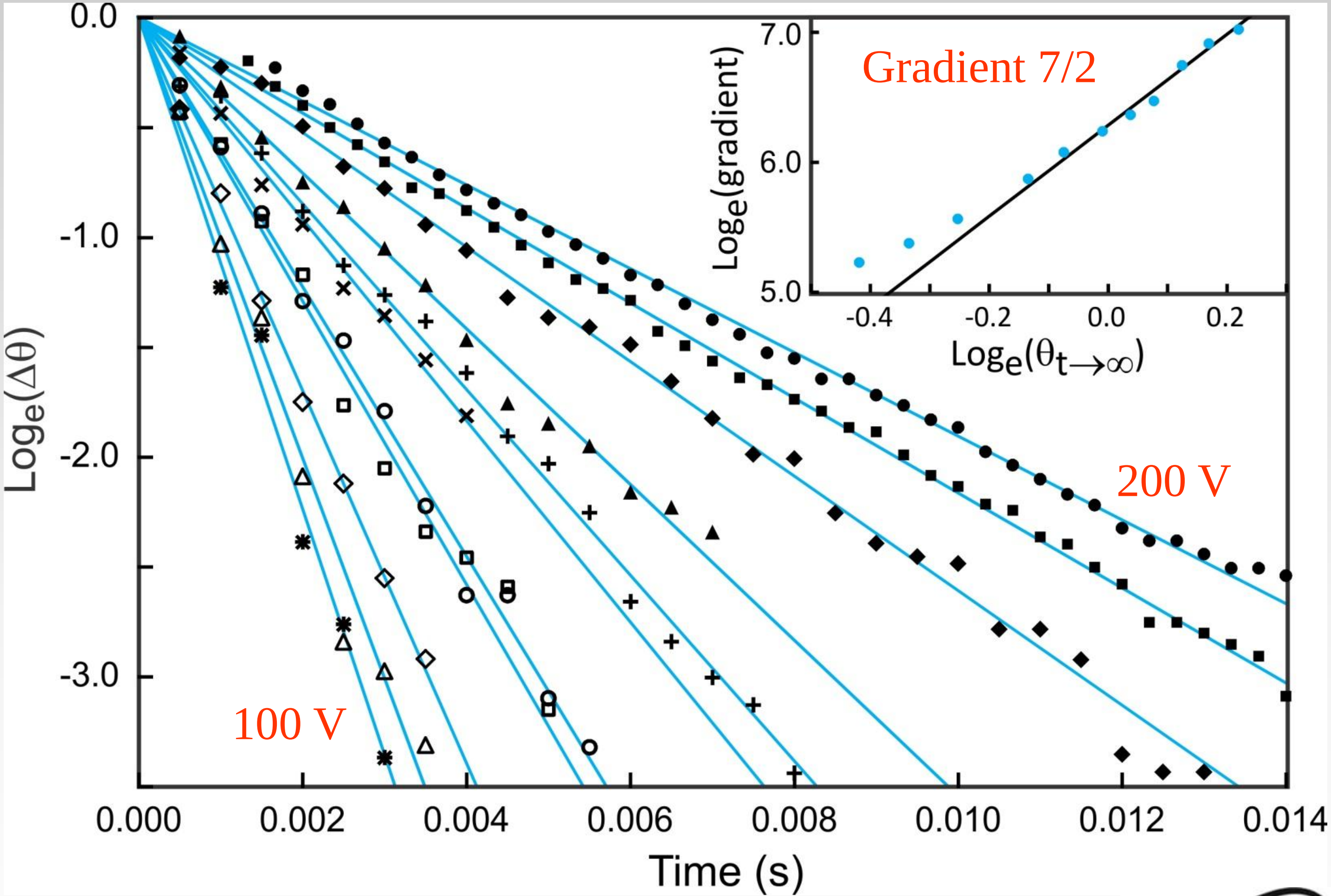
Recall: Observed Stripe Dynamics



10 kHz sinewave, 1, 2 propylene glycol ,electrode pitch p = 160 μm,
Initial contact angle 78°

27 December 2013

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



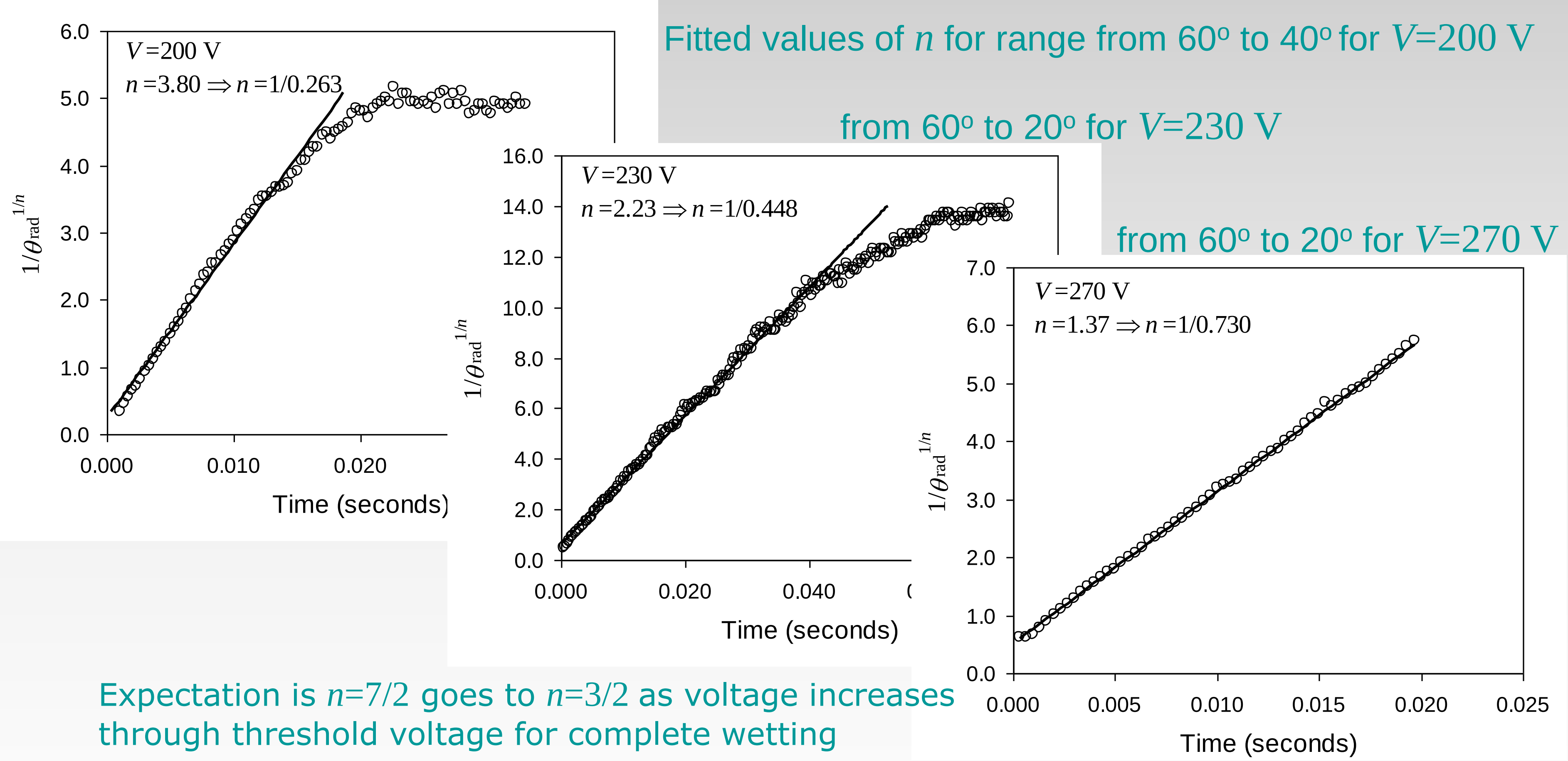
Exponential approach to equilibrium with correct scaling with voltage

Tanner’s Law for Complete Wetting ($V \sim V_{Th}$)

Fitted values of n for range from 60º to 40º for $V=200$ V

from 60º to 20º for $V=230$ V

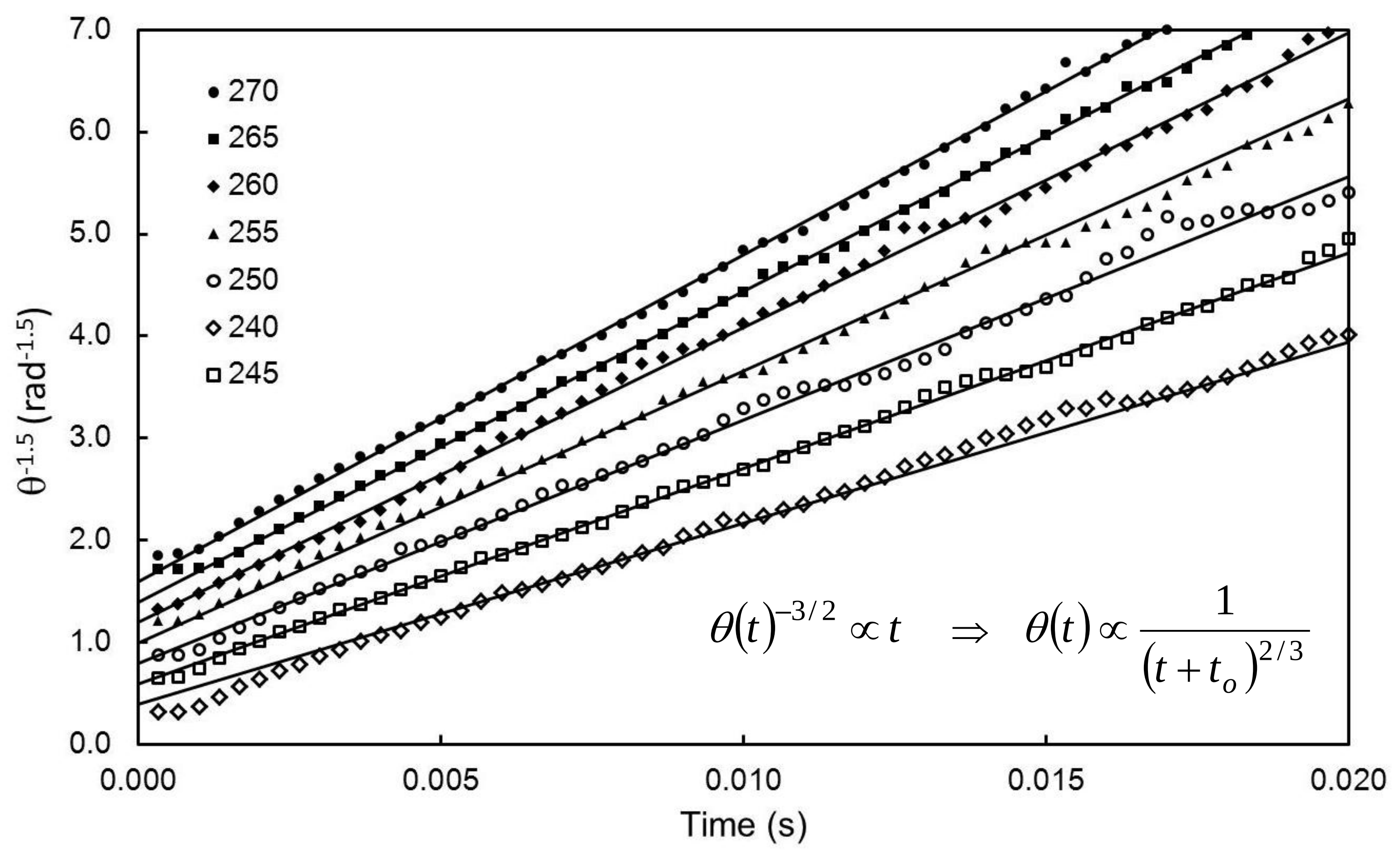
from 60º to 20º for $V=270$ V



Expectation is $n=7/2$ goes to $n=3/2$ as voltage increases through threshold voltage for complete wetting

Change of exponent as voltage induces transition to complete wetting

Superspreading ($V>V_{Th}$)



Superspreading with correct exponent of 3/2 for θ (or 2/3 for time)

Summary

1. Developed theory for L-DEP driven (dielectro-) wetting and spreading
2. Removes requirements of EWOD for solid insulator, direct electrical contact or conducting liquid
3. Modelled equilibrium liquid response for droplets and wrinkled films – analogous equation to EWOD for droplets
4. Created fast switching, polarisation independent, phase grating using oils with pitch down to 20 μm
5. Modelled dynamics of droplets and stripes
6. Observed three droplet spreading regimes for stripes including voltage induced super-spreading

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The End

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