Electrowetting of Liquid Marbles

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Overview

1. Super-Hydrophobicity

2. Electrowetting of Droplets

3. Electowetting on S/H Surfaces

4. Liquid Marbles (and Puddles)

5. Electrowetting of Liquid Marbles

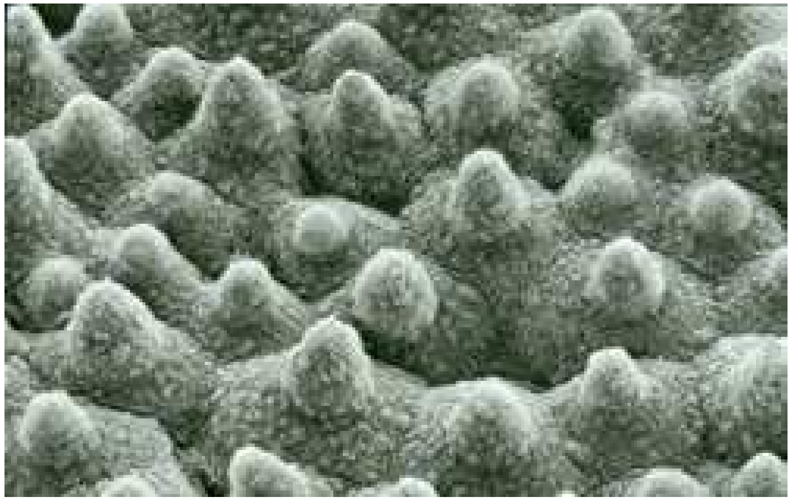
Super-Hydrophobicity

The Sacred Lotus Leaf

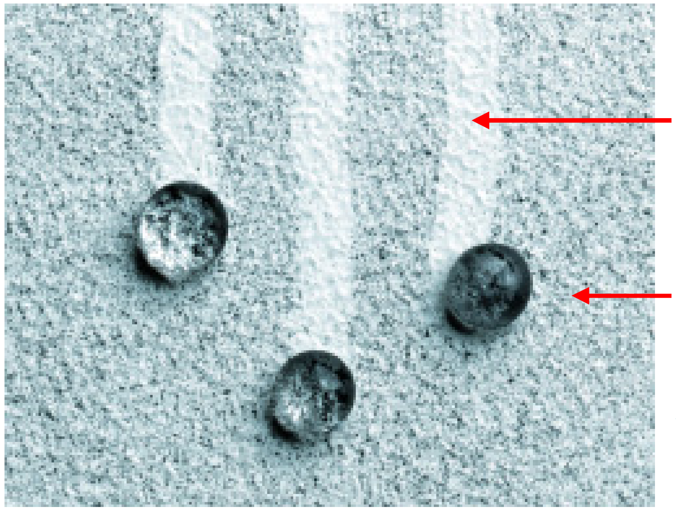
Plants

- Many leaves are super-water repellent
- The Lotus plant is known for its purity
- Super-hydrophobic leaves are self-cleaning under the action of rain

SEM of a Lotus Leaf



Self-Cleaning



Dust cleaned away

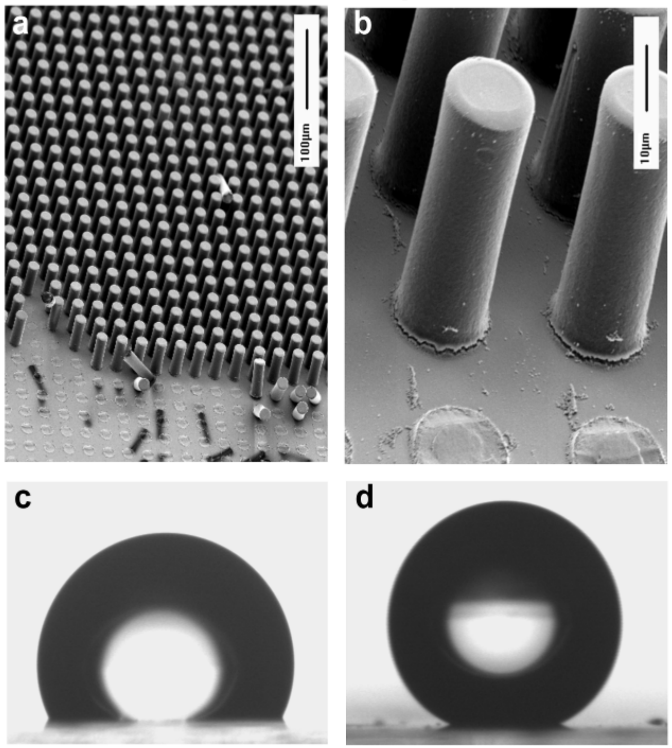
Dust coated droplet

A “proto-marble”

Acknowledgement   Neinhuis and Barthlott

Surface Structure

Effect on Water



a), b) Pillars *D*=15 µm, *L* = 2*D*

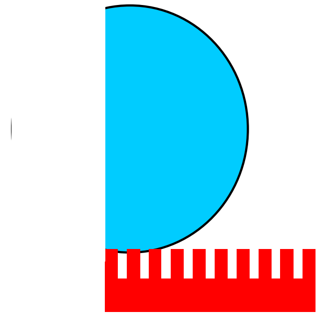
c) Flat and hydrophobic

d) Tall and hydrophobic

"Skating" Droplets

Composite air-solid surface

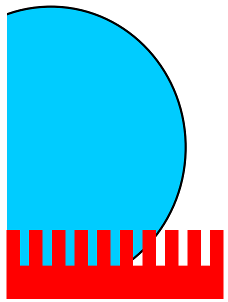
Low hysteresis: "Slippy" surface



"Penetrating" Droplets

Based on roughness

Large hysteresis: "Sticky" surface

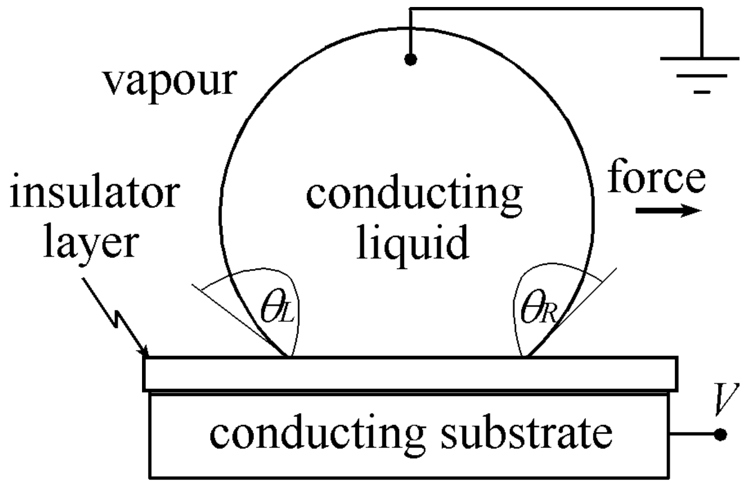


Reference Shirtcliffe *et al*, J. Micromech. Microeng. 14 (2004) 1384-1389.

Electrowetting

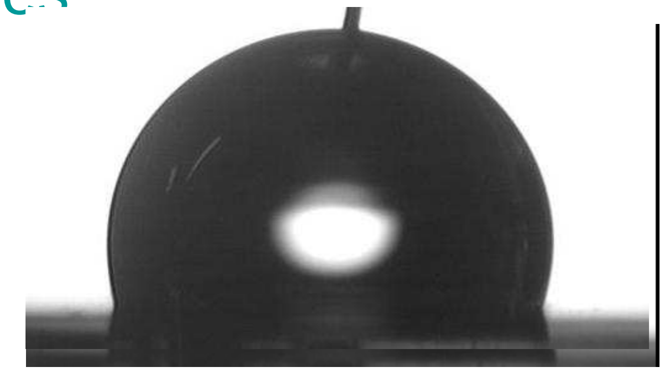
Electrowetting on Dielectric (EWOD)

- Electrowetting Principle
  - Conducting liquid on electrical insulator on conducting substrate



  - Applying voltage electrically charges solid-liquid interface (i.e. a Capacitive effect)
  - Droplet spreads and contact angle reduces

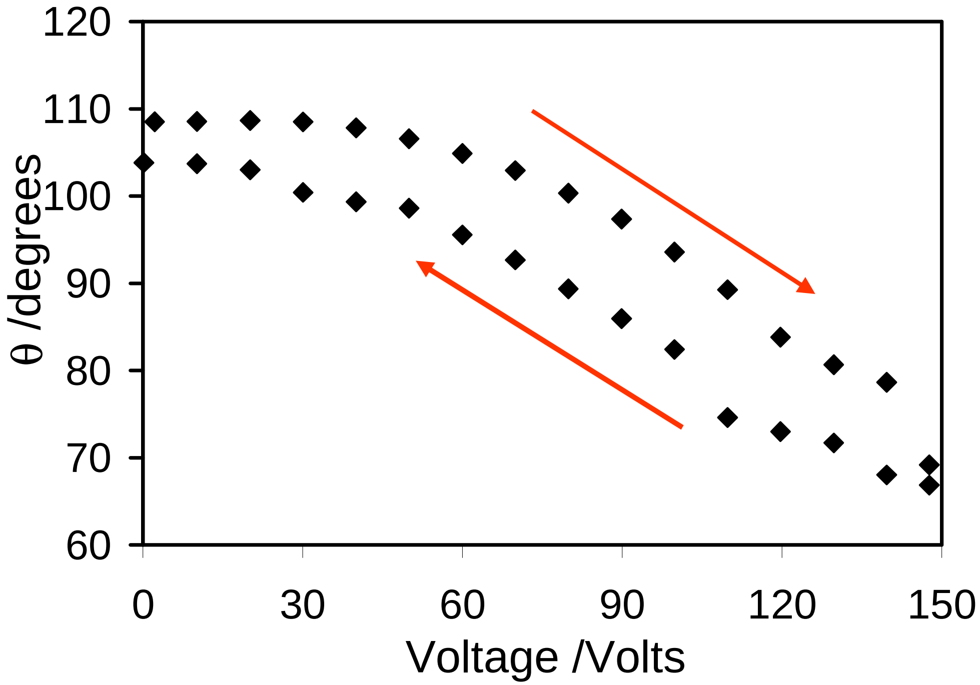
$$\cos\theta_e(V) = \cos\theta_e(0) + CV^2/2\gamma_{LV}$$



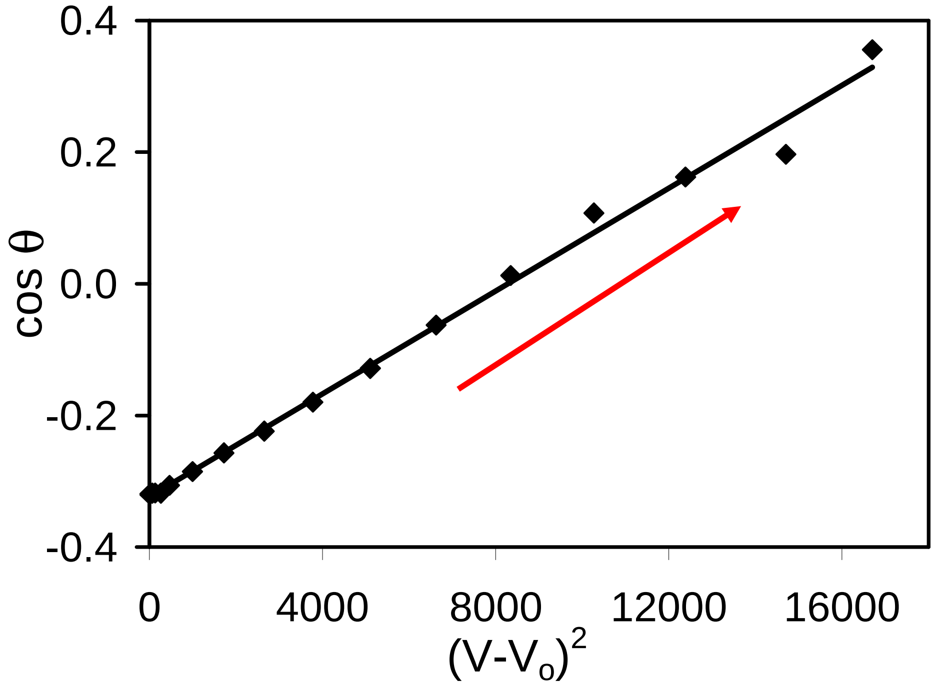
  - Difference in angles at edge of droplet reflects an actuating force

Results on Flat Hydrophobic SU-8

Contact Angle



Fitting



1. Threshold voltage of around 30 V
2. Contact angle hysteresis of around 5°
3. Offset voltage in fit (~ 18.4 V) represents charging

Electrowetting on S/H Surfaces

Super-hydrophobicity & EWOD

- Idea
  - Use S-H to gain high initial contact angle $\theta\uparrow$
  - Use electrowetting to tune over full angular range $\theta\downarrow$

- Thin Insulator, d
  - Capacitive energy $\propto V^2/d$
  - Thin insulator for lower voltages

- Electrowetting
  - Applying voltage causes electrocapillary pressure into surface texture ("Penetrating")

Contradiction 1

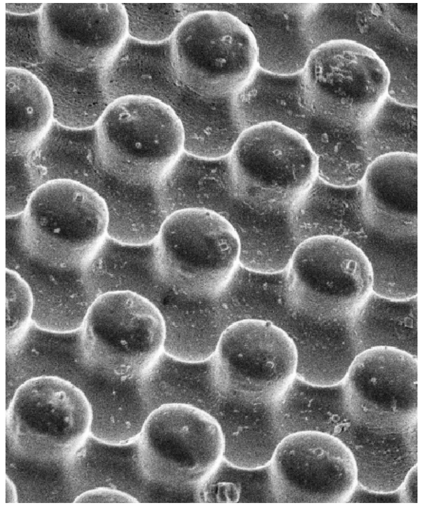
But Super-H via patterning insulator → high aspect ratio

Contradiction 2

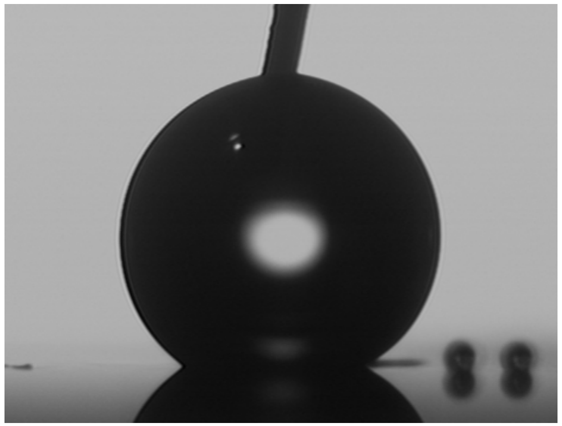
But low hysteresis requires "Skating"

Irreversible Electrowetting

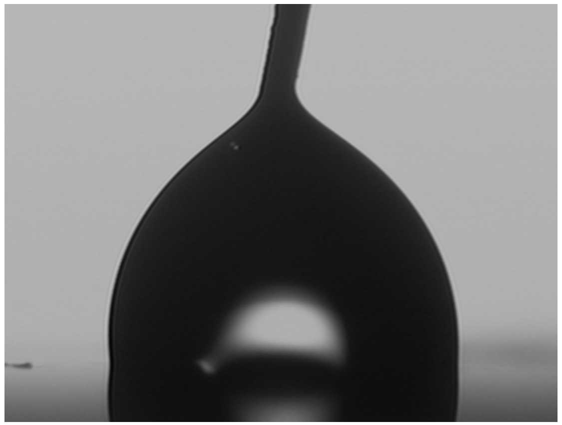
- Lithographic System
  - Ti/Au on glass, SU-8 Pillars 7 μm diameter, 15 μm centre-centre, height 6.5 μm (roughness $r \approx 1.64$)
  - Spin coated Teflon AF1600 (not perfect, $r_{estimate} \approx 1.87$)
  - Droplets of deionised water with 0.01M KCl, DC voltage by steps up to 130 V



Initial Shape



Applied Voltage

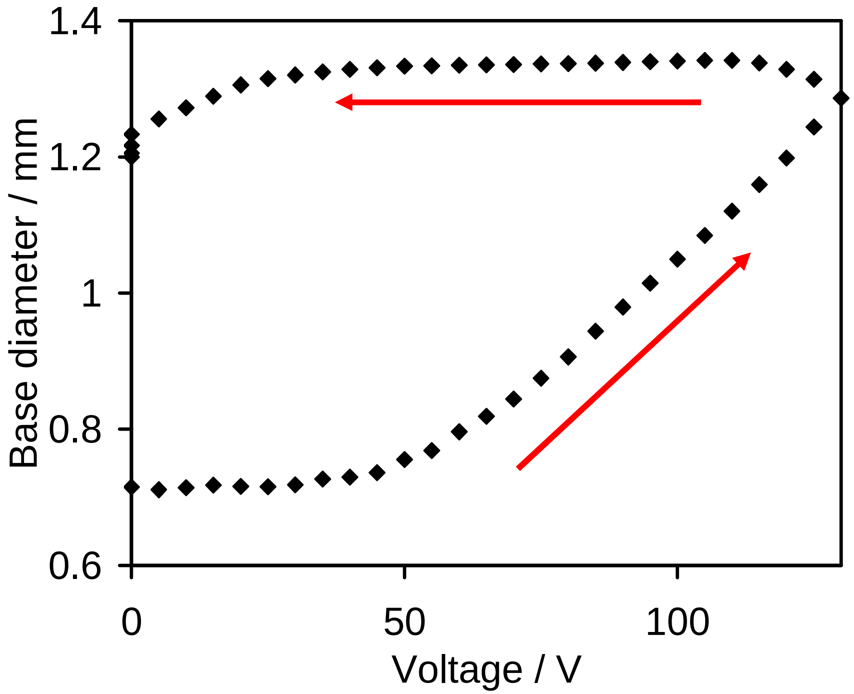


Voltage Removed

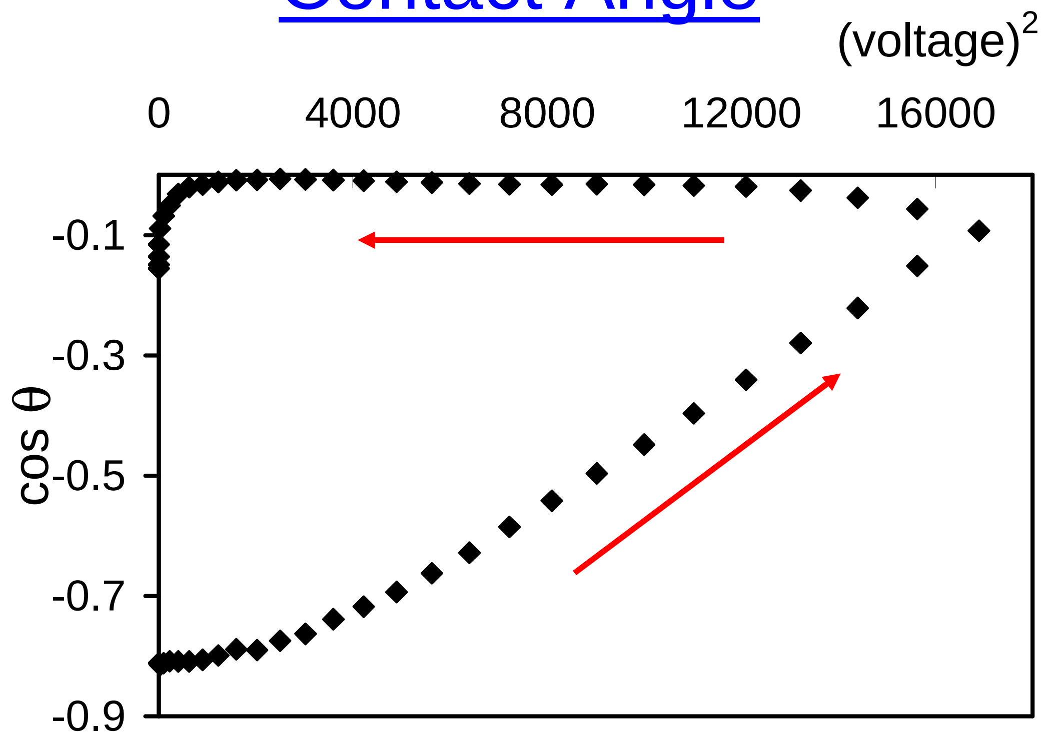
152^{o} —— *irreversible* ——→ 114^{o}

Results on SU-8 Pillars

Base Diameter



Contact Angle



1. *Threshold* voltage (~ 45 V) before droplet spreads
2. *Irreversible* on removal of voltage

Reference Herbertson *et al*, Sens. Act. A (2006).

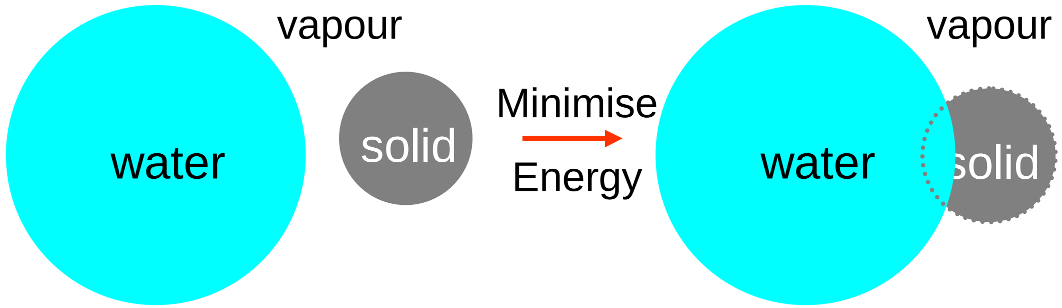
Principles of Liquid Marbles

Liquid Marbles

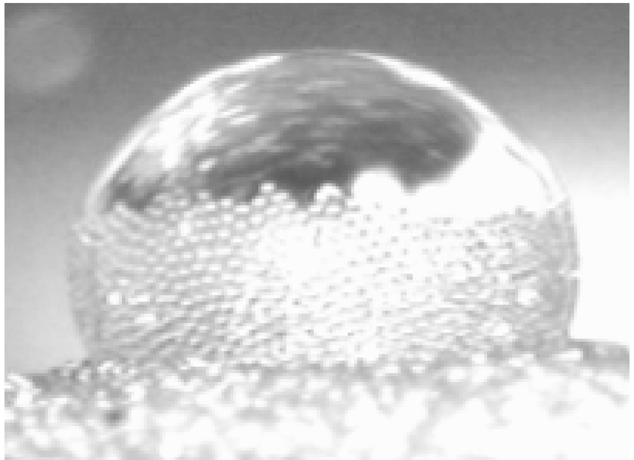
- Hydrophobic Grains Adhere to the Solid-Liquid Interface

Water droplets can self-coat to create perfect marbles

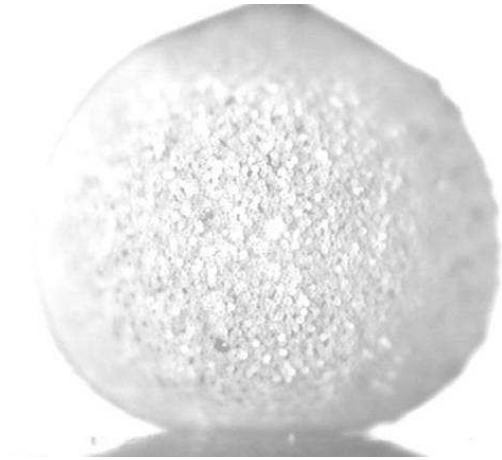
Ideal "droplet" (180º contact angle) which rolls around on a solid surface



Large Silica

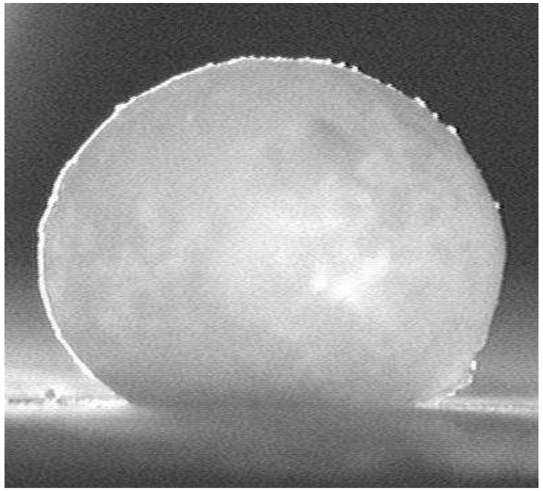


Lycopodium



Lycopodium grains are 15-19 µm, but monolayers can be achieved

Silica Powder

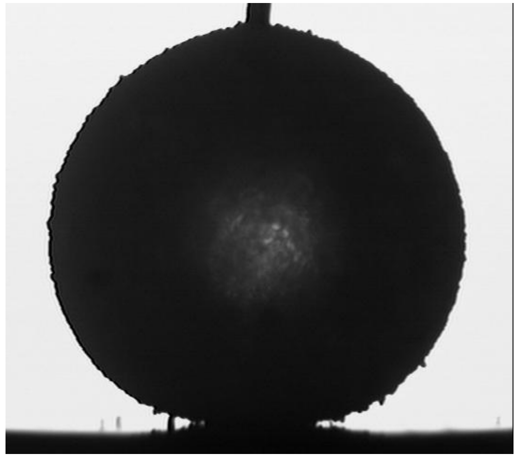


Silica grains are sub-µm, but layer is thick

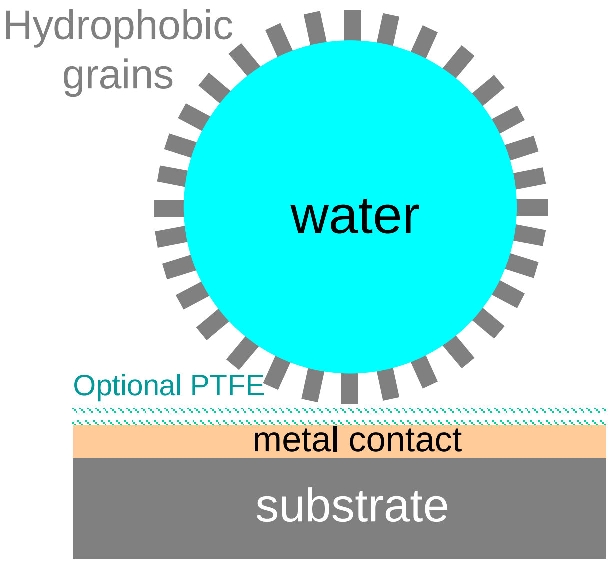
Acknowledgement David Quéré, College de France, Paris.

Electrowetting of Liquid Marbles

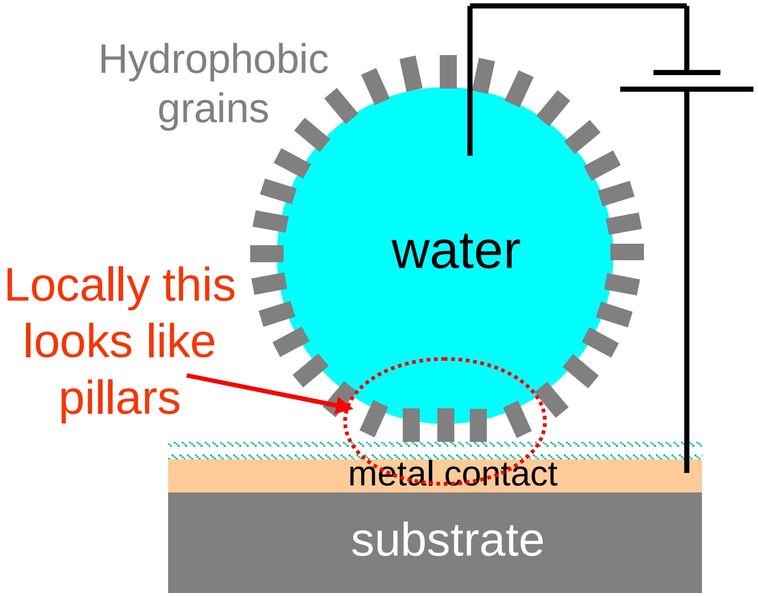
- Reversibility Idea
  - Make the solid “pillars” adhere more to the liquid than to the substrate
  - Provides insulating “pillars” conformal to the liquid shape
  - More hydrophobic grains “stick out” further (i.e. taller pillars)
  - Spin coated Teflon AF1600 on substrate to stop complete breakthrough if granular coating is breached



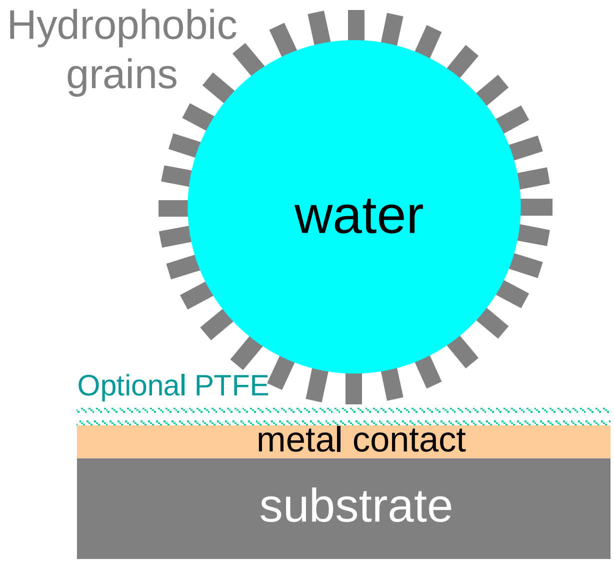
Initial Shape



Apply Voltage



Remove Voltage



Theory of Liquid Marbles

Minimise total energy of a spherical cap

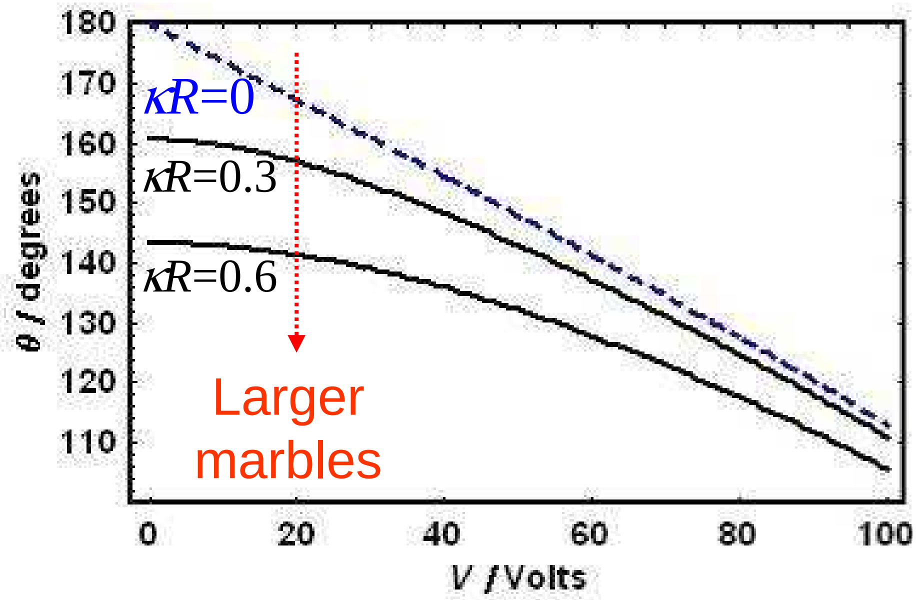
$$\cos\theta = \cos\theta_e + (\kappa h)^2/6 + CV^2/2\gamma_{LV}$$

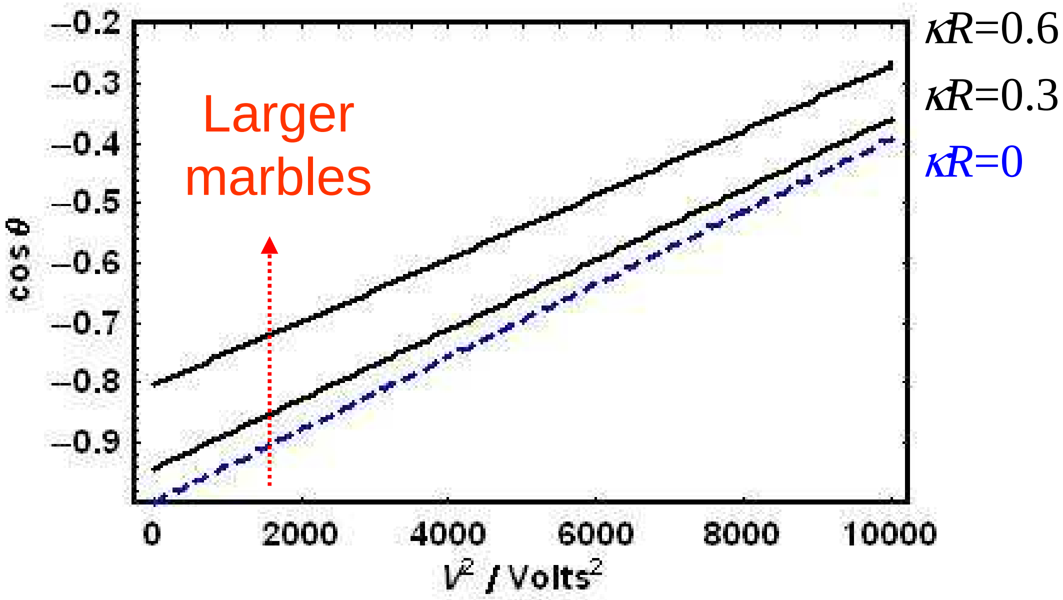
From surface energy
-1 for marble

Gravitational energy gives a drop size factor with $h = h(\theta)$, so non-linear

Electrowetting from capacitive energy

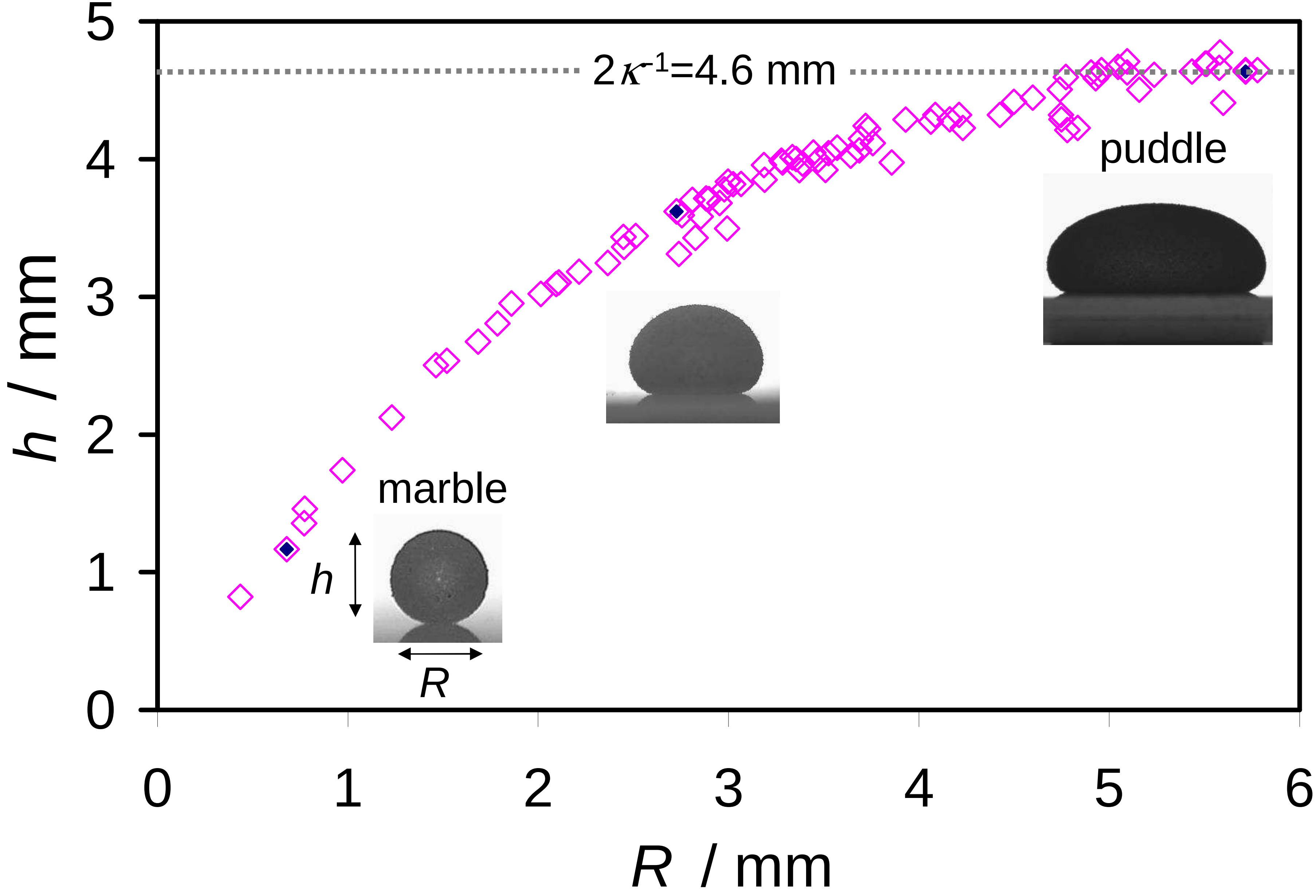
Numerical Results





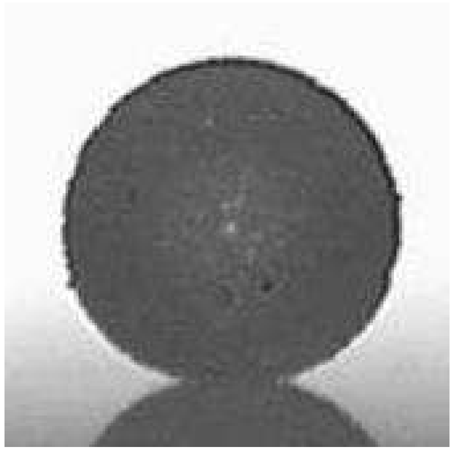
Experiments on Liquid Marbles

Size Data (Lycopodium)

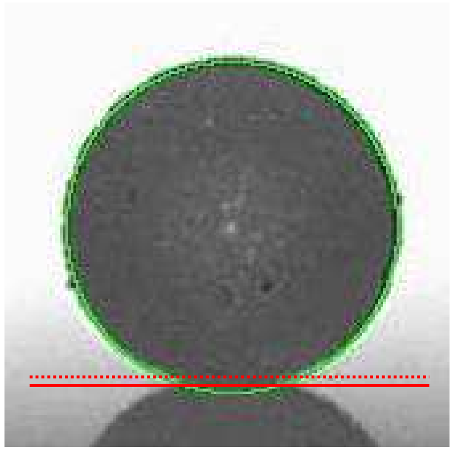


Accuracy of Measurements

Marble



Circular Fit



Comments

Almost perfect circle $\theta \rightarrow 180^o$

Spherical radius, *R*, is OK

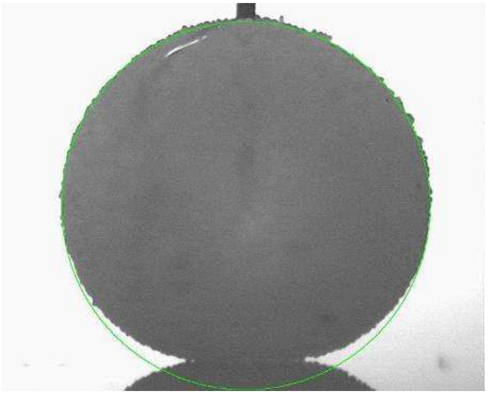
Baseline difficult due to grains in "skin"

Contact radius *r*, is sensitive to baseline

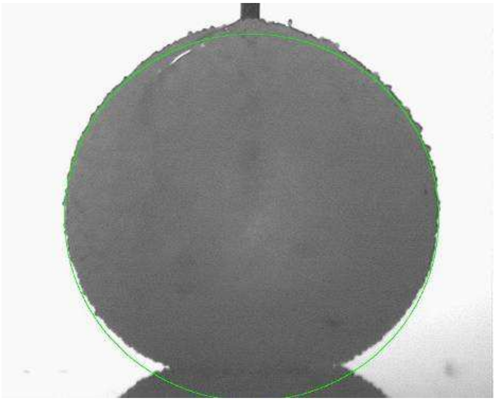
Contact angle θ, is sensitive to baseline

With Needle/Contact Wire

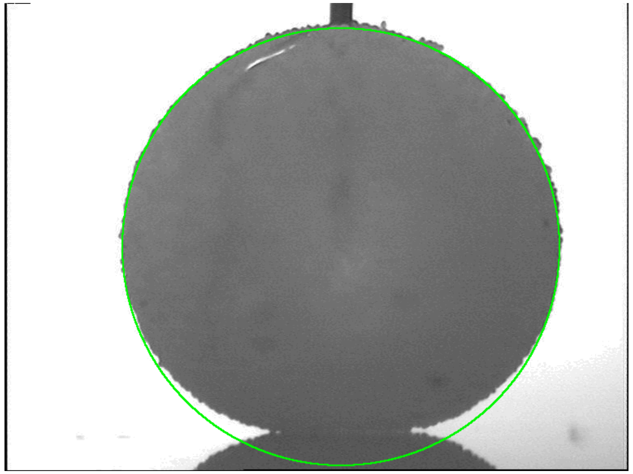
No Voltage



With Voltage

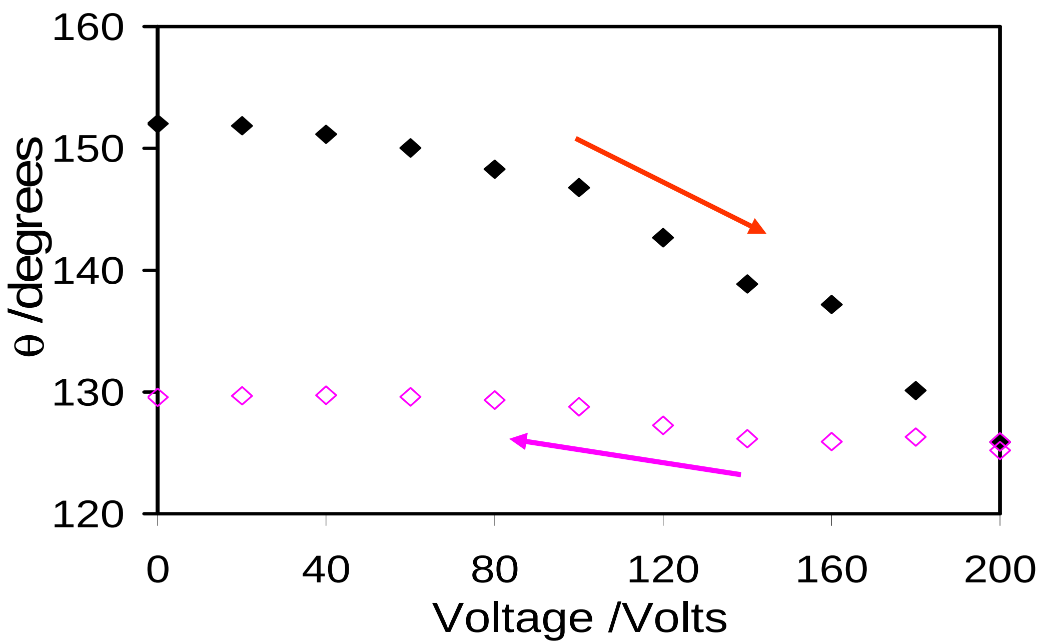


Reversibility – Low V Cycle

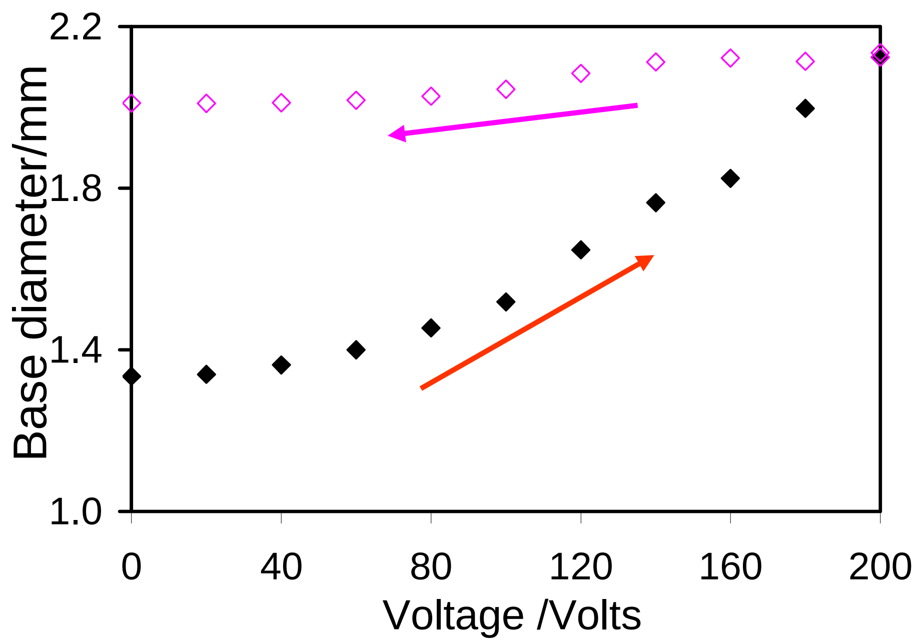


Results using Hydrophobic Lycopodium

Contact Angle



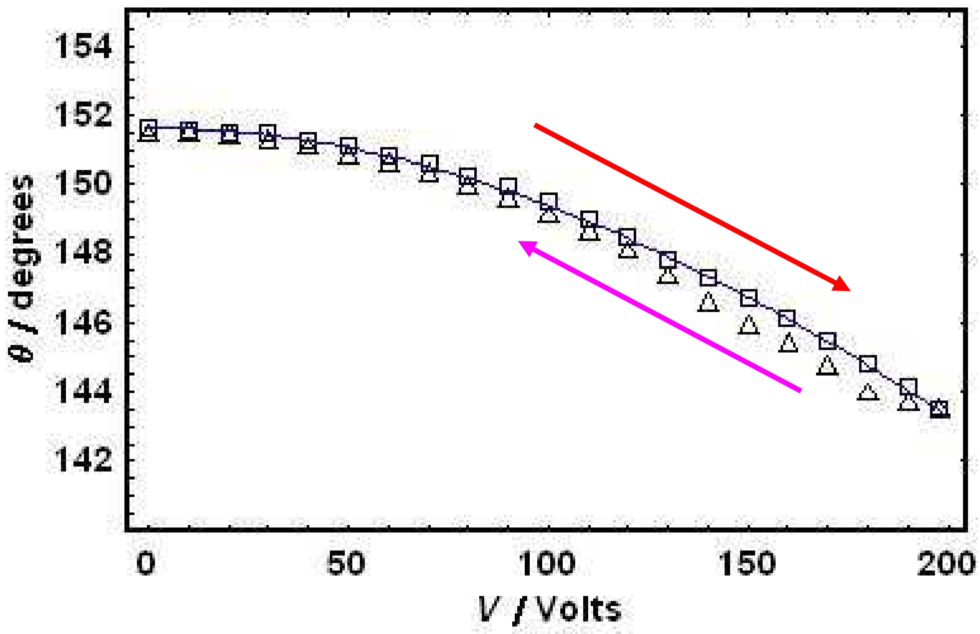
Base Diameter



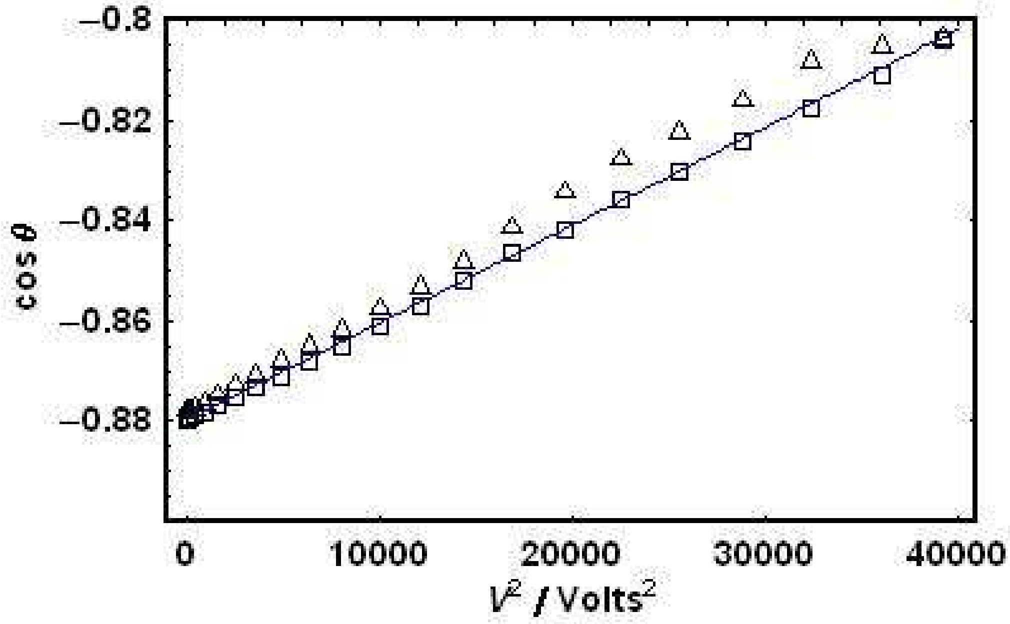
1. No significant threshold voltage
2. Reversibility is compromised at highest voltages due to contact area becoming pinned – "*liquid breakthrough*"

Results using Hydrophobic Silica

Contact Angle



Fitting



1. *No threshold* voltage
2. Virtually *no* contact angle *hysteresis*
3. Current experiments show a limited range (155º to 130º)
4. Fit uses κR=0.45

Future Work

1. Structure of Liquid Marbles

   Greater stability

   Reduction of charging

   Size ranges for marbles/puddles

2. Droplet Motion

   Non contact mode of generating contact angle changes

   Droplet actuation – Different left v right side contact angles

   Magnetic powder

The End

Acknowledgements

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GR/S34168/01 – Electrowetting

EP/C509161/1 – Extreme soil water repellence

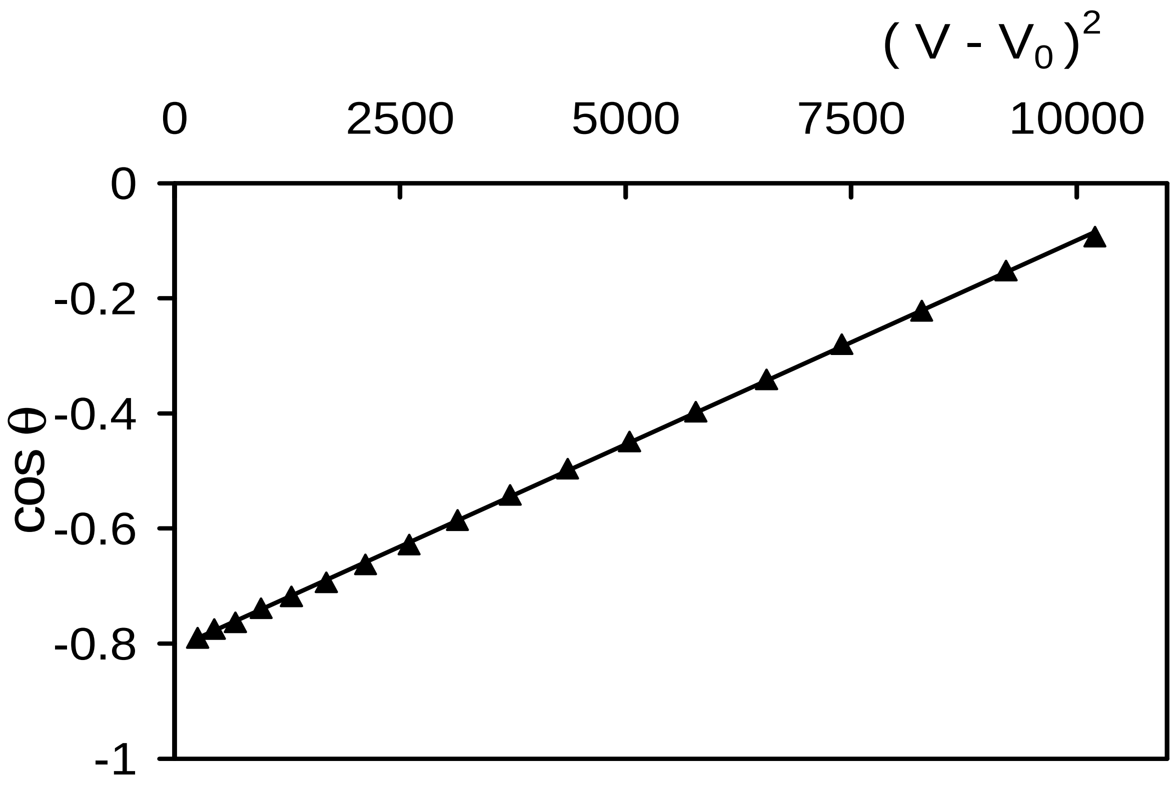
Dstl via EPSRC/MOD JGS

EU COST Action D19 - Chemistry at the nanoscale

Fitting of Results

- Increasing Voltage Half Cycle
  - Advancing droplet charges substrate before contact with liquid
  - Modified fitting equation to include a constant V_o

$$\cos\theta_e(V) = \cos\theta_e(0) + C(V-V_o)^2/2\gamma_{LV}$$



Interpretation

1. Conversion from "skating" to "penetrating" regime
2. V_o=28V represents charging
3. Fitted $\theta_e(0)$ gives Wenzel angle of 143º and predicts r=1.92 (SEM image 1.87)