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Symposium on "New Frontiers in Chemical & Biochemical Engineering“,
26-27 November 2009, @ CERTH, Thessaloniki, Greece

Micro-Drops and Charges:
From Young to Lippmann and beyond

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ELECTROWETTING

wetting enhancement

http://www.ee.duke.edu/Research/microfluidics/

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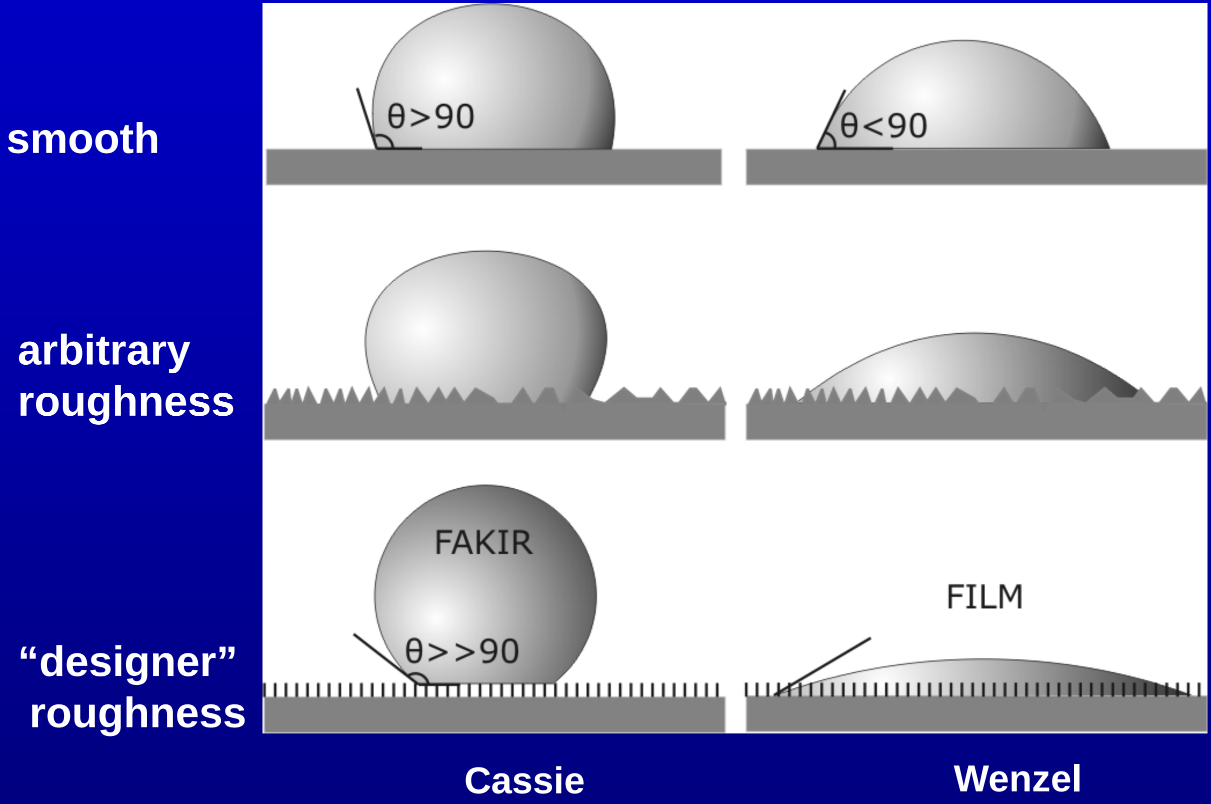
THE BROADER CONTEXT

Roughness design towards reversible non- / full-wetting surfaces: From Fakir Droplets to Liquid Films

The '**HYDROFAKIR**' project is approved for funding by the **European Research Council,** through an **IDEAS** Starting Grant awarded to **Dr. Thanasis Papathanasiou**. Duration: 5 years**.**



http://www.chemeng.ntua.gr/people/pathan/hydro.htm

- **the transition from Cassie to Wenzel is NOT reversible**
- **a 'kick' is required to recover the Cassie state**

AIM: design roughness + design 'kick' to make the transition reversible

IMPACT: self cleaning, tunable flow resistance, efficient liquid handling without mechanical parts, water collection from dew formation . . .

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The HYDROFAKIR key parts:
Design – Fabricate – Test

continuum modelling: Level Set Method

length scale: 10 μm

mesoscale modelling: Lattice Boltzmann Method

length scale: 1 μm

to study :

- equilibrium states
- dynamics
- stability analysis
- mechanism of transition
- free energy barrier

surface

perturbation

(obtained from theory)

uniform heating ‘kick’
(minimize required energy)

function
- shape
- amplitude

technique
- distributed light illumination
- electrolysis
- other

(energy efficiency, biocompatibility)

- find surface topography that minimizes the energy barrier

(dependence of the energy barrier on roughness features such as pillar shape, size, distance)

- find perturbation that destabilizes the Wenzel state

(among the admisssible perturbations find those with higher growth rate)

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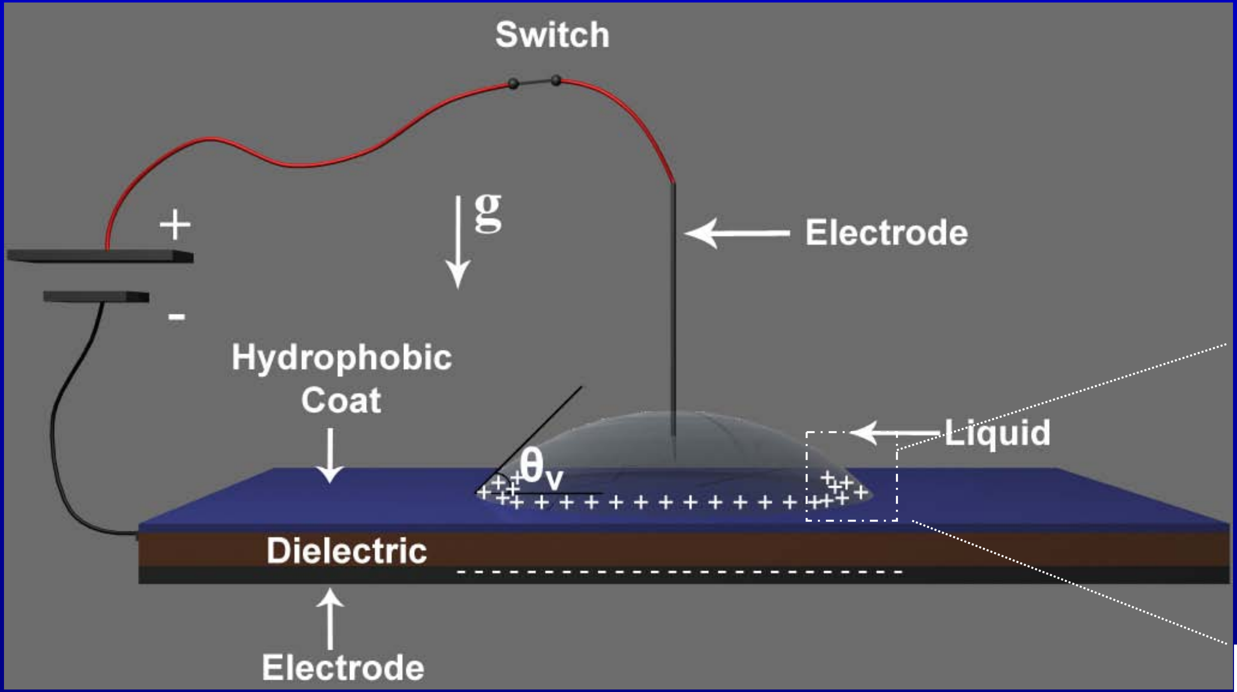
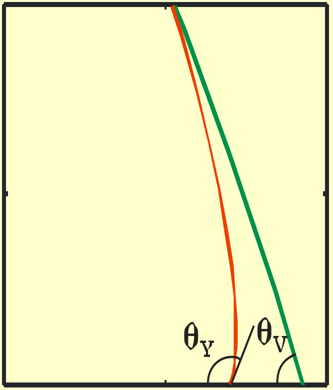
ELECTROWETTING IN A SESSILE DROP

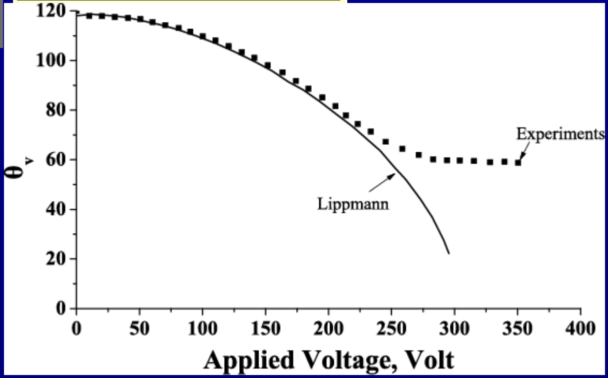


Lippmann's equation:

$$\cos\theta_V = \cos\theta_y + \frac{1}{\gamma_{LV}}\frac{1}{2}cV^2,$$

$$c = \varepsilon\varepsilon_o/d$$

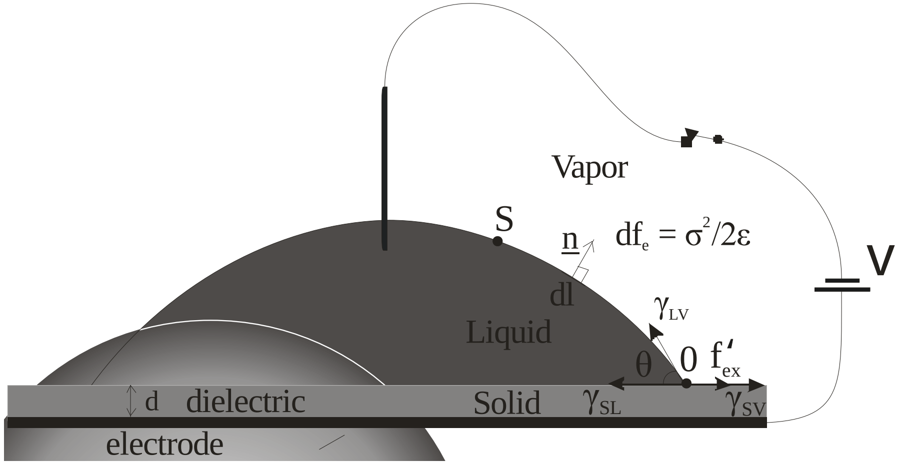




Limiting phenomena in electrowetting

- contact angle saturation
- droplet emission around the contact line

How electrowetting modifies the wettability ?



$$f_e = \int_{LV} \frac{\sigma^2}{2\varepsilon} dl = \ldots = \frac{\varepsilon V^2}{2d\cos\theta}$$

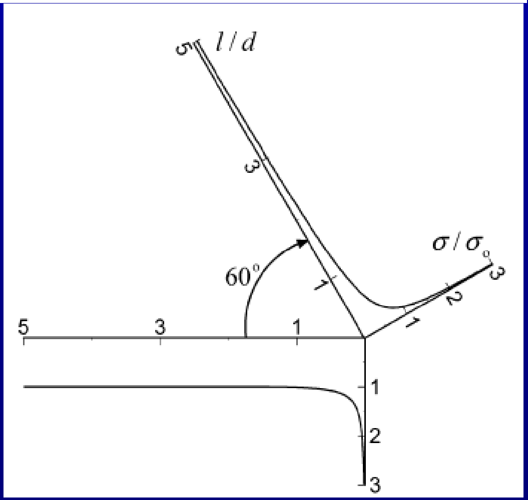
↗ $\text{x - component}: f_{ex} = \frac{\varepsilon V^2}{2d}$

↘ $\text{y - component}: f_{ey} = \frac{\varepsilon V^2}{2d}\cot\theta$

Young's eqn: $\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta_y$

Lippmann's eqn: $\gamma_{SV} + \frac{\varepsilon V2}{2d} = \gamma_{SL} + \gamma_{LV}\cos\theta_V$

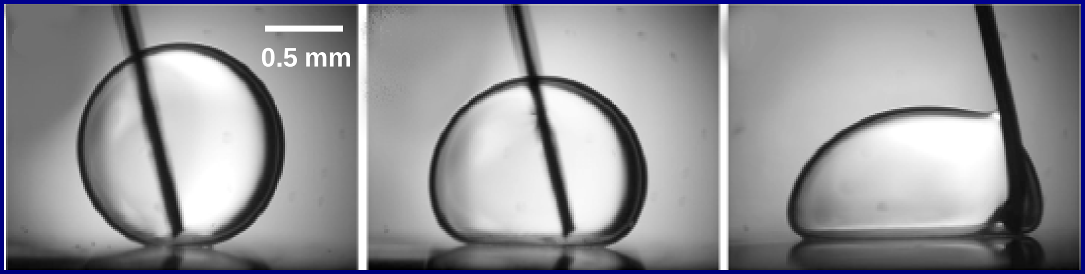
Electric Force at the TPL: $f_{e_{SLV}} = \lim_{s\to 0} \int_0^S \frac{\sigma^2}{2\varepsilon} dl = \ \ldots \ = 0$



surface charge density close to the TPL (three phase contact line)

Kang, *Langmuir* **18,** 10318 (2002)

experimental evidence

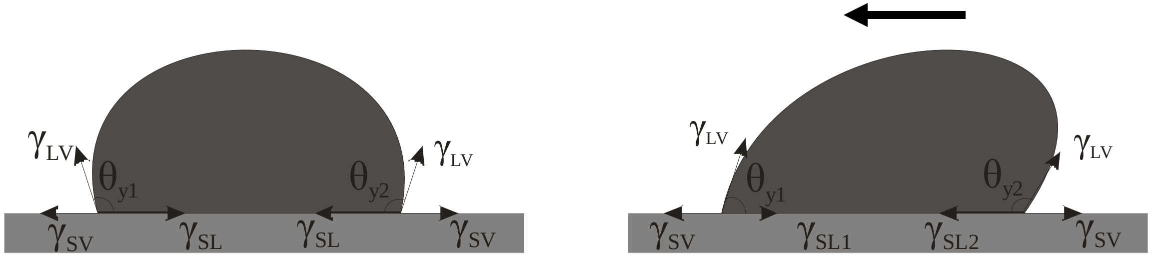


V = 0 **$V = V_1$** **$V = V_2 > V_1$**

Mugele & Buehrle, *J. Phys.: Condens. Matter* **19,** 375112 (2007)

DROPLET ACTUATION

Young's eqn: $\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta_y$



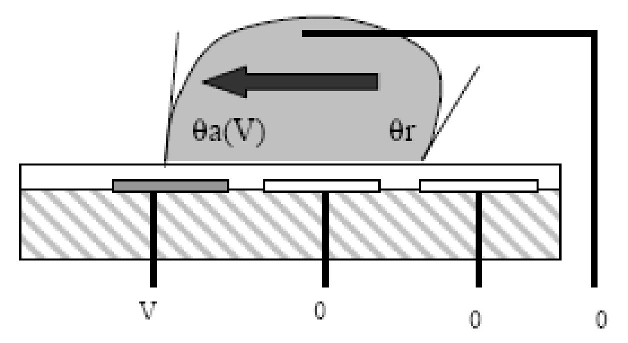
$\theta_{y1} = \theta_{y2}$

$\gamma_{SL1} < \gamma_{SL2} \Rightarrow \theta_{y1} < \theta_{y2}$

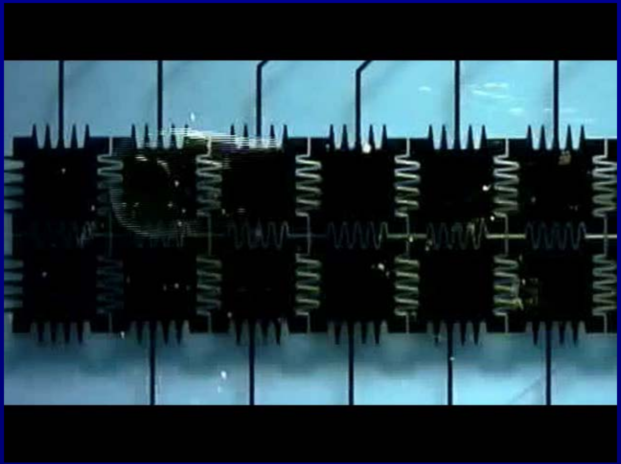
droplet movement due to wettability gradient

ELECTROWETTING ACTUATION

principle of operation



it works pretty nice !



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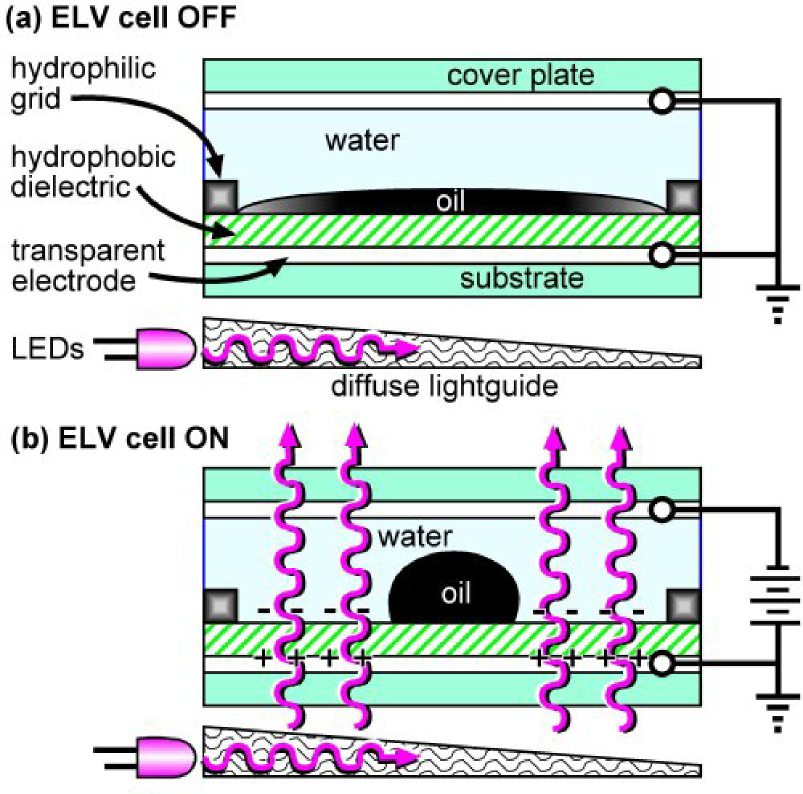
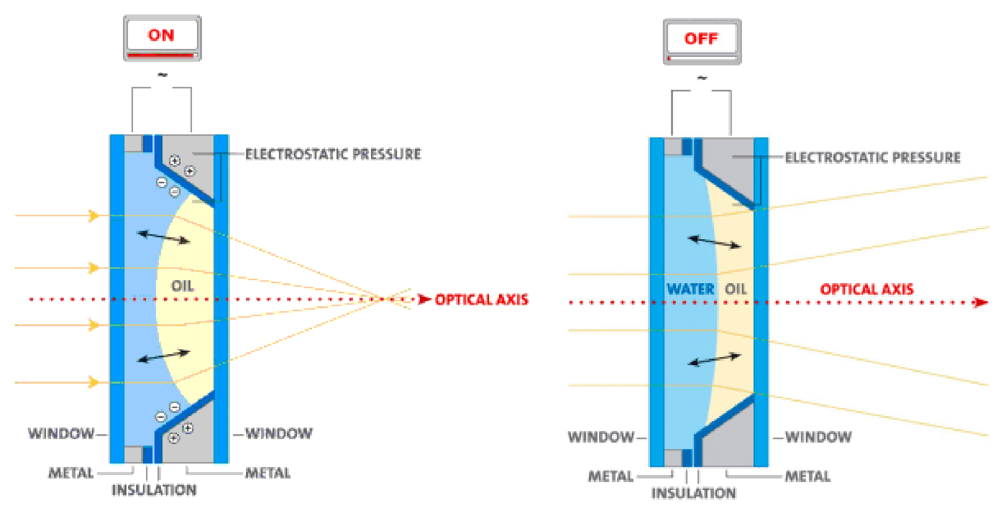
APPLICATIONS

They will soon appear in consumer devices
(microcameras in mobile phones, computer screens)

electrowetting display



liquid lens with variable focal length



Berge & Peseux, *European Physical Journal E* **3**, 159 (2000).
Hayes & Feenstra, *Nature* **425**, 383 (2003).

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BASIC QUESTIONS

- **What’s beyond Young and Lippmann ?**

- **is the exact solution of the electro-hydrostatic problem enough for explaining the contact angle saturation ?**

- **if no, how can we use it to extract information and guide further analysis?**

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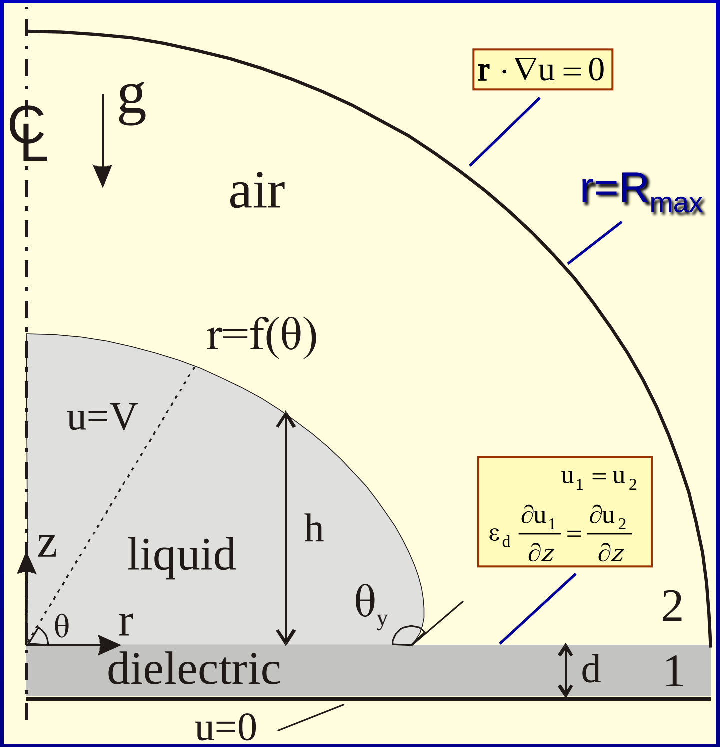
ELECTRO-HYDROSTATICS

governing equations and boundary conditions



Young-Laplace equation

$$-g\delta\rho h + \varepsilon_0 E^2/2 + \gamma_{lv} C = K$$

Field distribution

Electric potential: $E \equiv \nabla u$

$\nabla^2 u = 0$ **In the dielectric, in the air**

Volume constraint

$$\int_0^{\pi/2} f^3 \sin\theta d\theta = 2$$

BOUNDARY CONDITIONS:

FIELD CONDITIONS - ASYMPTOTIC CONDITIONS - INTERFACIAL CONDITIONS

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THE COMPUTATIONAL PROBLEM

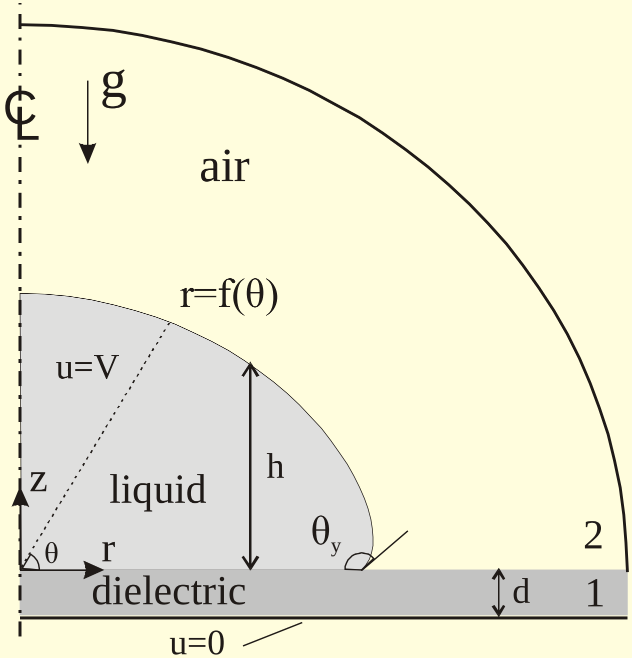
- **TWO-DIMENSIONAL**

$f(\theta)$ free surface location

$u_2(r,\theta)$
$u_1(r,z)$
electric potential

- **NONLINEAR**

- **FREE BOUNDARY**



THE EQUATIONS ARE SOLVED FOR f, u SIMULTANEOUSLY

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WHY SATURATION?

- H. J. J. Verheijen and M. W. J. Prins, *Langmuir* **15**, 6616 (1999).
  trapping of charge
- M. Vallet, B. Berge and L. Vovelle, *Polymer* **37**, 2465 (1996).
  air ionization at the contact line
- E. Seyrat and R. A. Hayes, *J. Appl. Phys.* **90**, 1383 (2001).
  increasing breakdown strength, improves electrowetting performance
- V. Peykov, A. Quinn and J. Ralston, *Colloid Polym. Sci.* **278**, 789 (2000).
- A. Quinn, R. Sedev and J. Ralston, J. Phys. Chem. B **109**, 6268 (2005).
  saturation when $E_{sl} = 0$
- B. Shapiro et al., *J. Appl. Phys.* **93**, 5794 (2003).
  relative conductivity of the media is important

- A. G. Papathanasiou and A. G. Boudouvis, *Appl. Phys. Lett.* **86**, 164102 (2005).
  breakdown strength determines the onset of the saturation

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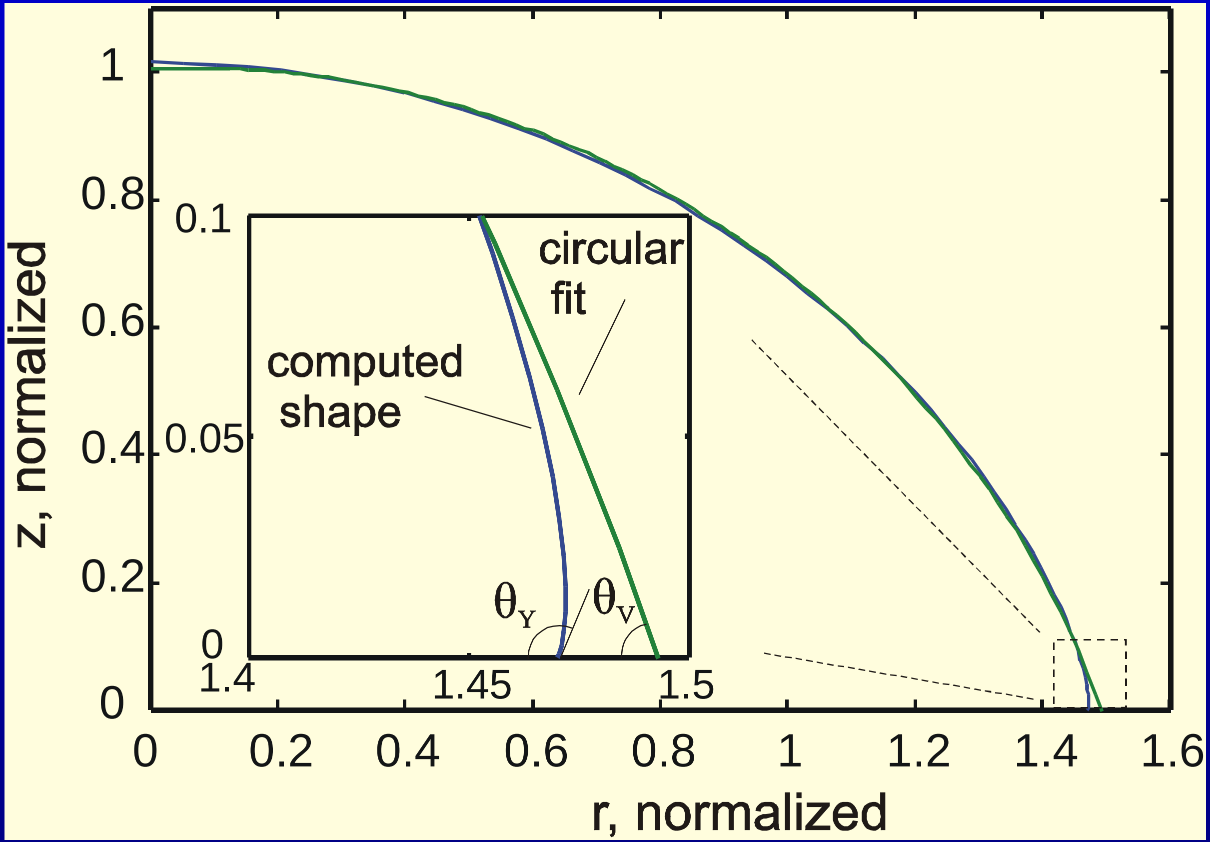
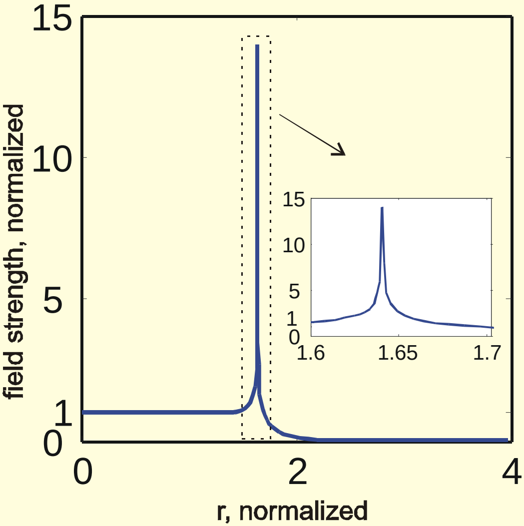
THE COMPUTED DROP SHAPE





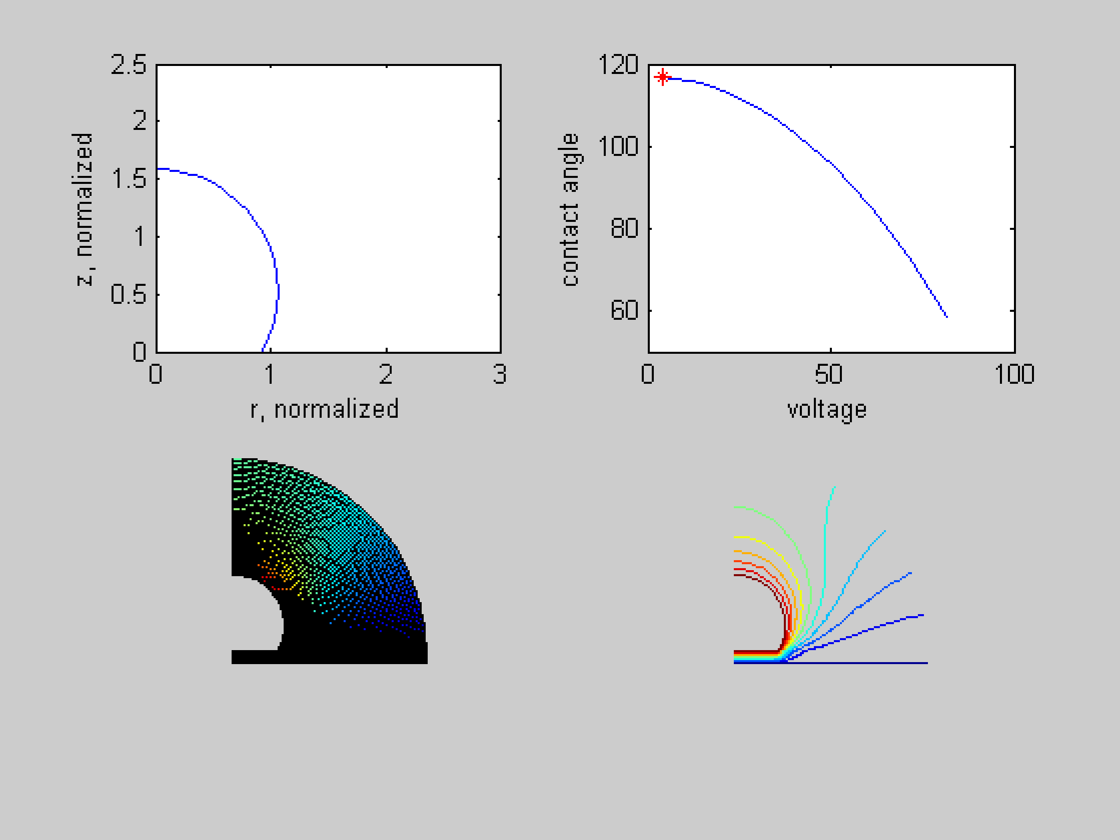
d = 1 μm SiO_2, $\varepsilon_r = 3.8$

γ_{lv}=0.072 N/m, water

$\theta_Y = 120^o$

$\theta_V = 70^o$ at V = 75V

SHAPE DEPENDENCE ON THE APPLIED VOLTAGE



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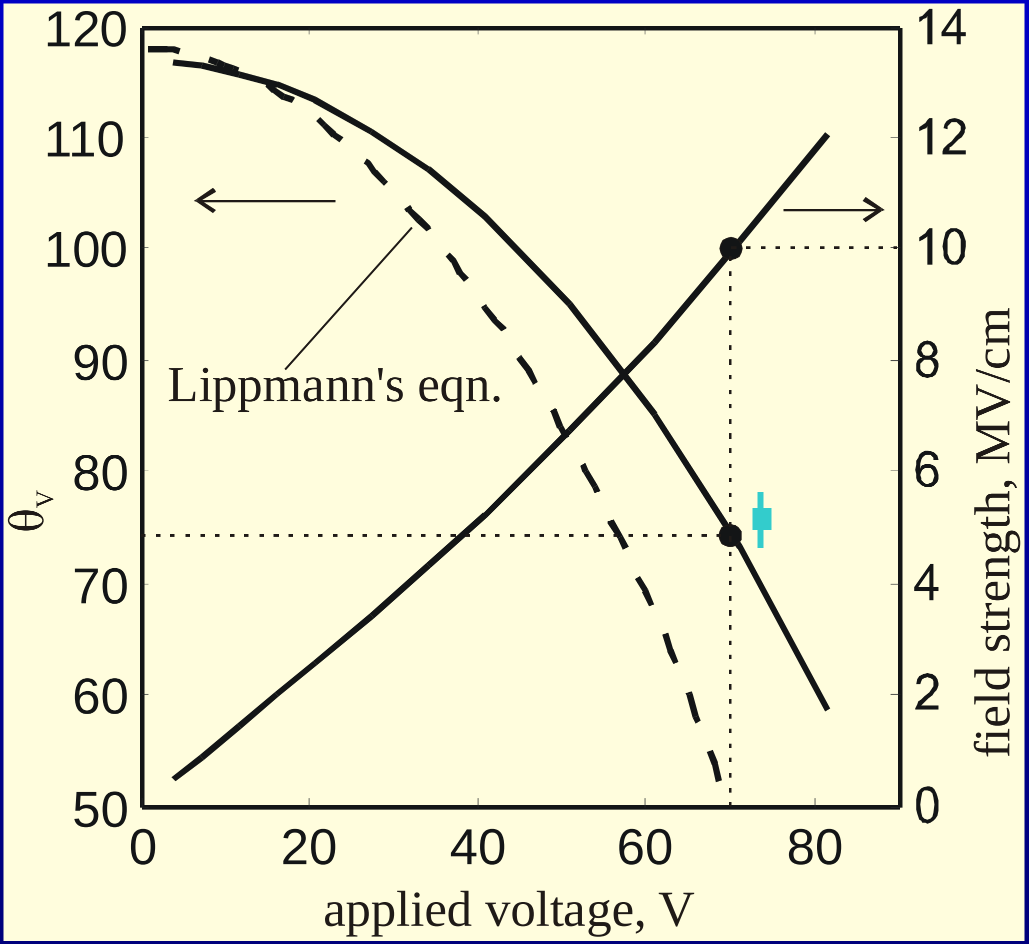
PREDICTING THE ONSET OF THE SATURATION



d = 1 μm SiO_2, ε_r = 3.8
E_{bd} = 10 MV / cm
γ_{lv}=0.072 N/m, water
θ_{sat} ~ 75° at V ~ 75 V

Papathanasiou & Boudouvis, *Applied Physics Letters* **86**, 164102 (2005).

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More findings
More questions

If the main cause of the saturation is the local breakdown of the dielectric at the three phase contact line then :

a) how can we show it experimentally ?

b) how can we improve our computational analysis to predict the asymptotic stabilization of the contact angle past the saturation?

c) what can we do to inhibit the saturation and improve electrowetting ?

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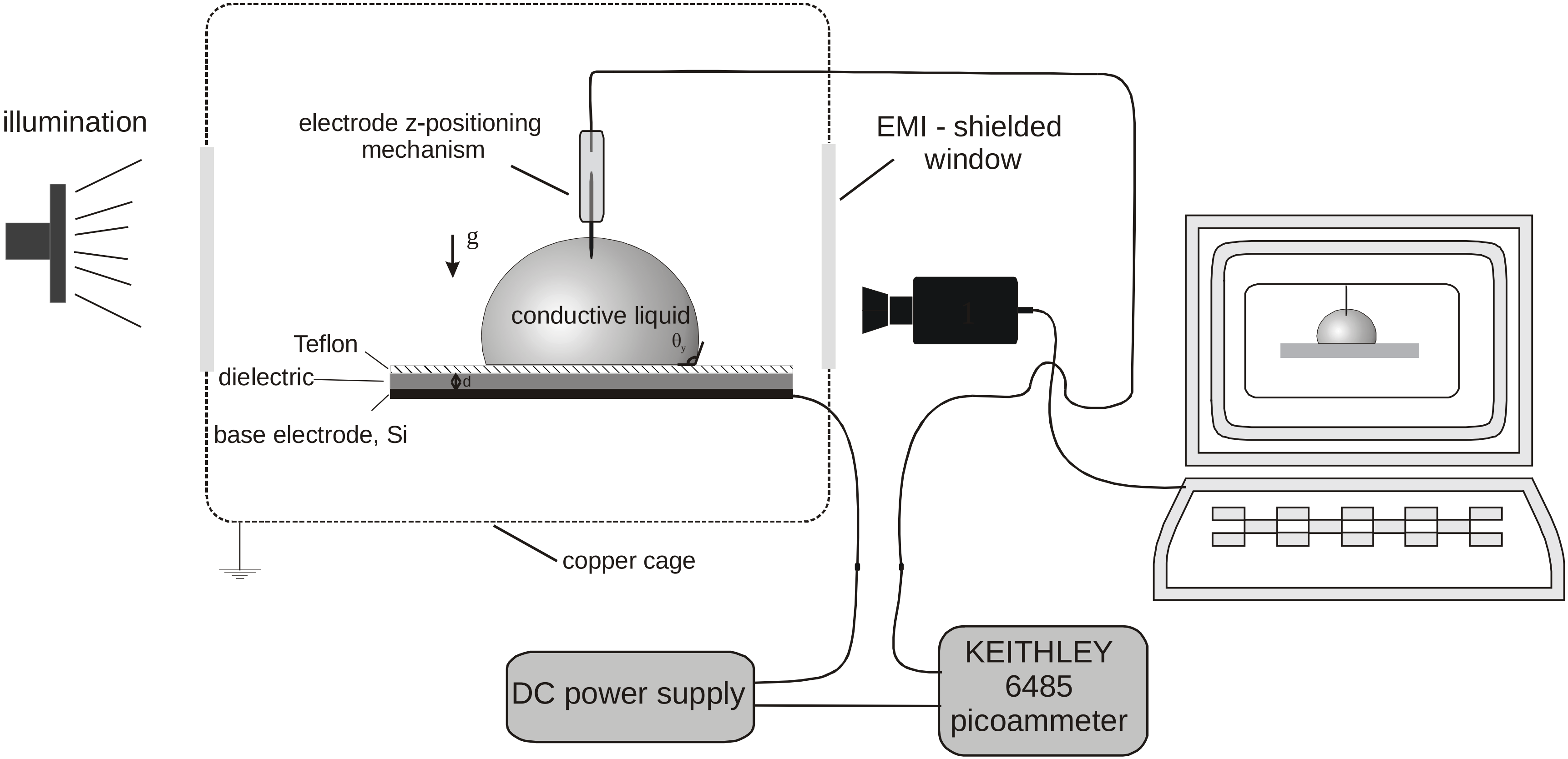
EXPERIMENTS

(the setup)



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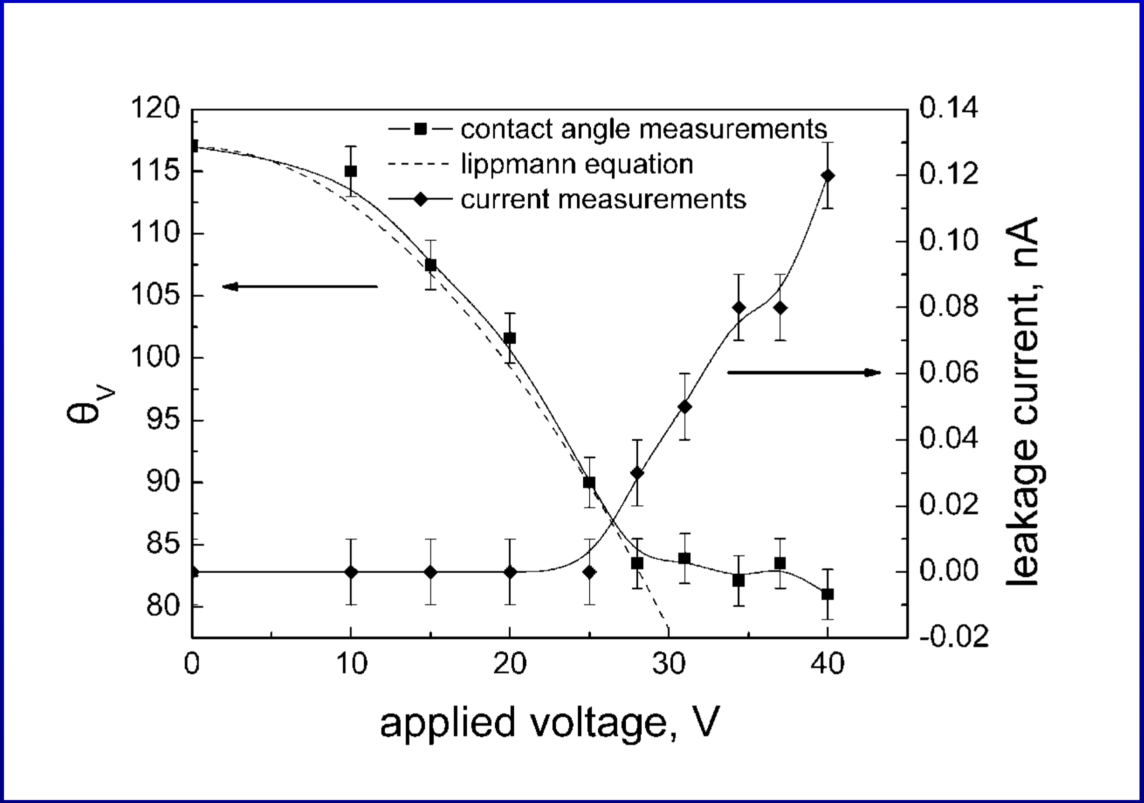
LEAKAGE CURRENT MEASUREMENTS



if the contact angle saturation is connected with local dielectric breakdown then significant increase of the leakage current is expected !

d = 130 nm SiO_2, $\varepsilon_r = 3.8$

γ_{lv}=0.072 N/m, water

$\theta_Y = 117^o$

Papathanasiou, Papaioannou & Boudouvis, *Journal of Applied Physics* **103**, 034901 (2008).

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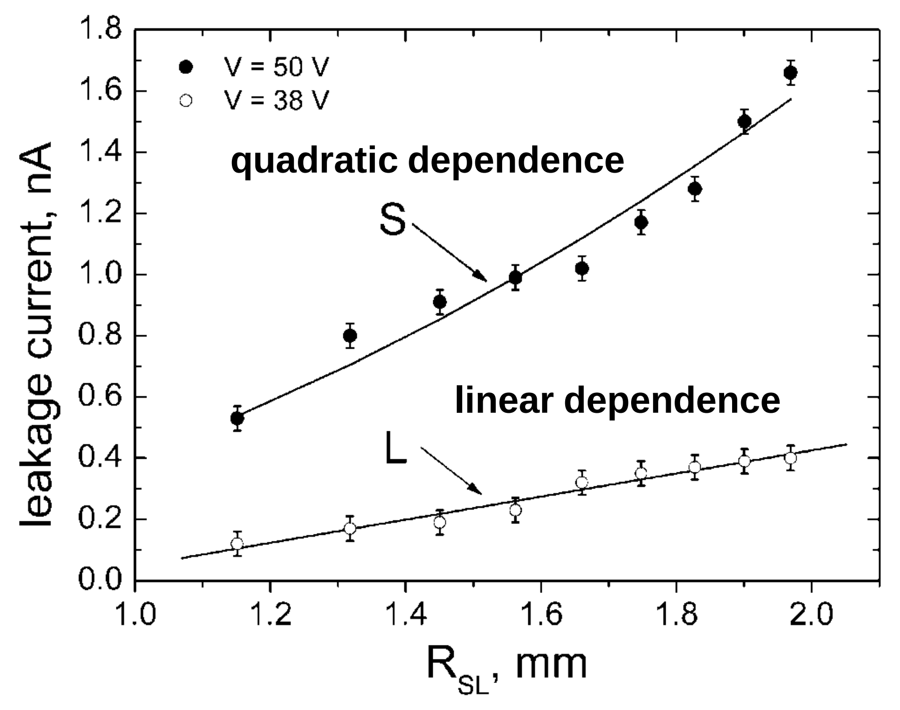
Is the breakdown localized at the contact line ?



d = 500 nm, TEOS,

ε_r = 3.8

γ_{lv}=0.072 N/m, water

θ_Y = 117^o

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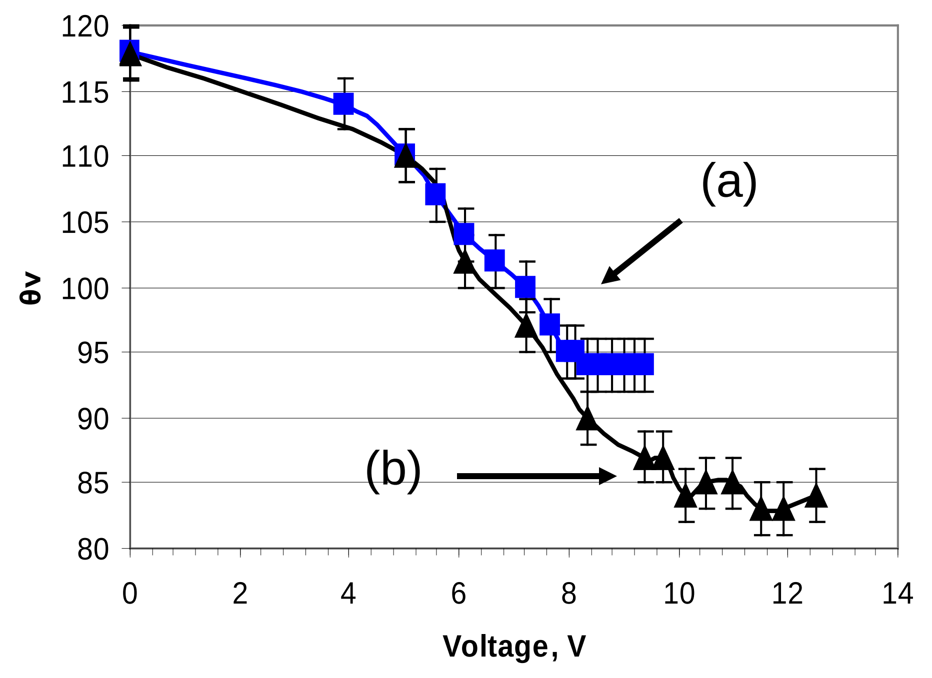
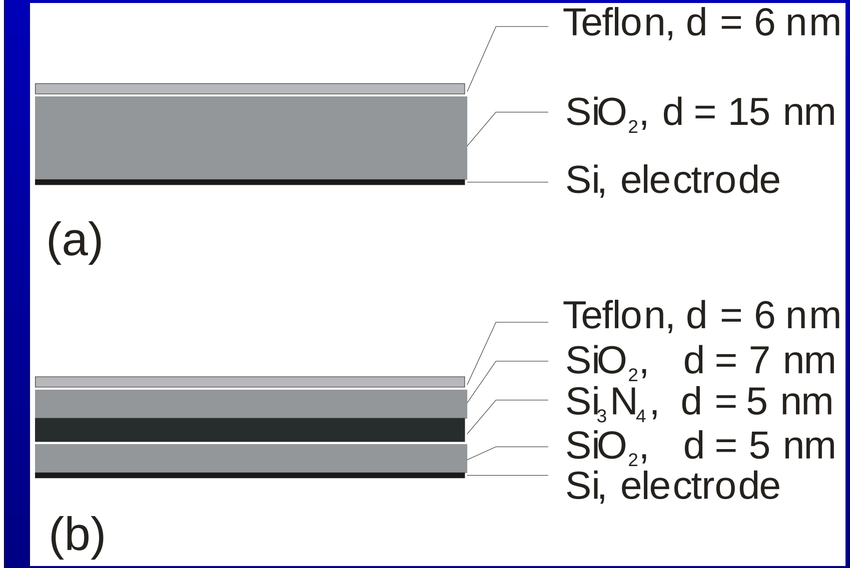
MULTILAYER vs SINGLE-LAYER DIELECTRICS



γ_{lv}=0.072 N/m, water

θ_Y = 117^o



$E_{bd,\ ONO} > E_{bd,\ SiO_2}$ *

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* Holland, *IEEE Trans. Nucl. Sci.* **42**, 423 (1995).

Nozaki & Giridhar, *IEEE Electron Device Lett.* **7**, 486 (1986).

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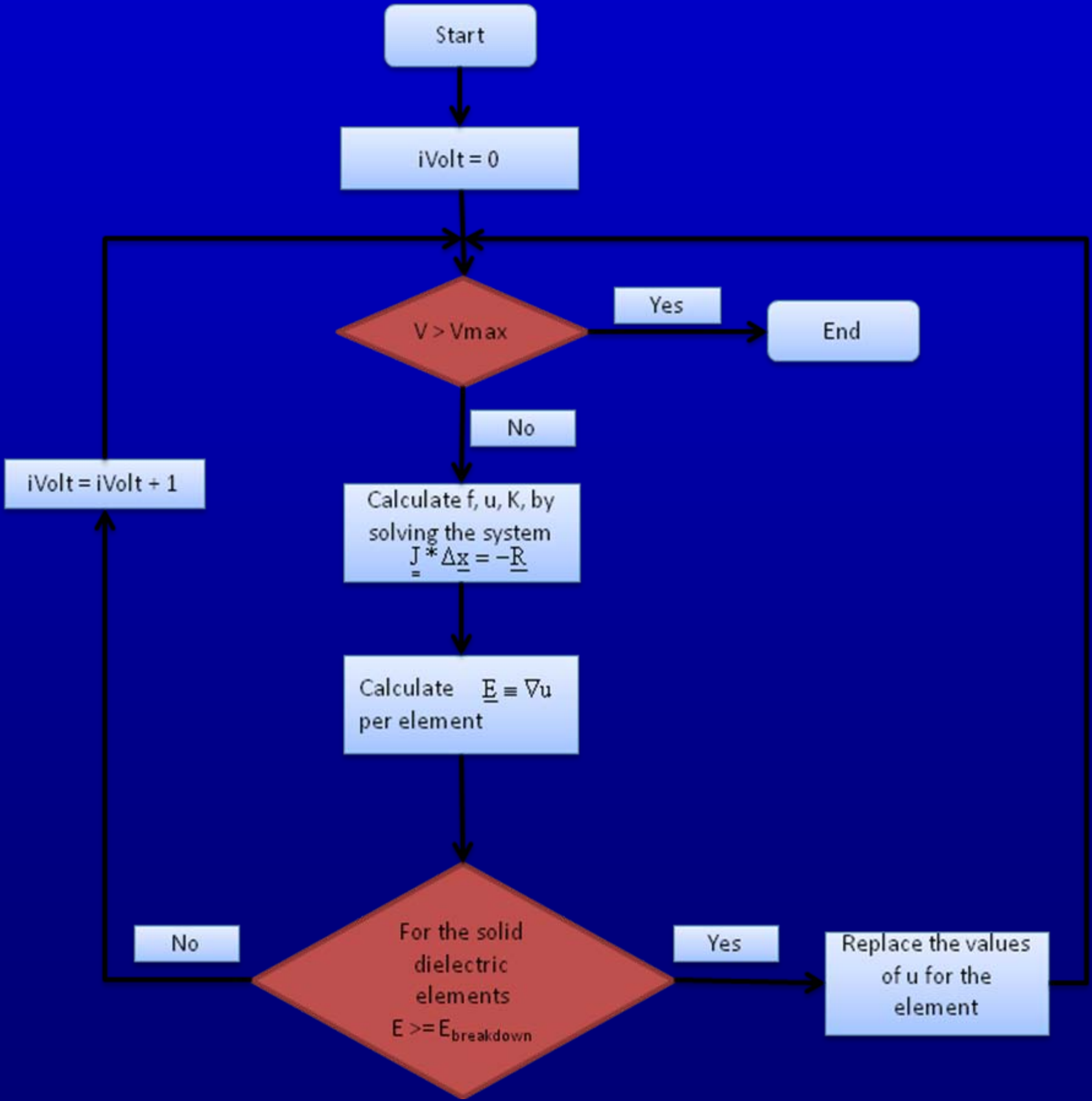
IMPROVING THEORETICAL PREDICTIONS

- the field strength cannot exceed the breakdwon strength of the solid dielectric
- regions with higher field strength are switched to conductive



Start

iVolt = 0

V > Vmax

Yes

End

No

Calculate f, u, K, by solving the system $\underline{\underline{J}} * \Delta\underline{x} = -\underline{R}$

Calculate $\underline{E} \equiv \nabla u$ per element

For the solid dielectric elements $E >= E_{breakdown}$

Yes

Replace the values of u for the element

No

iVolt = iVolt + 1

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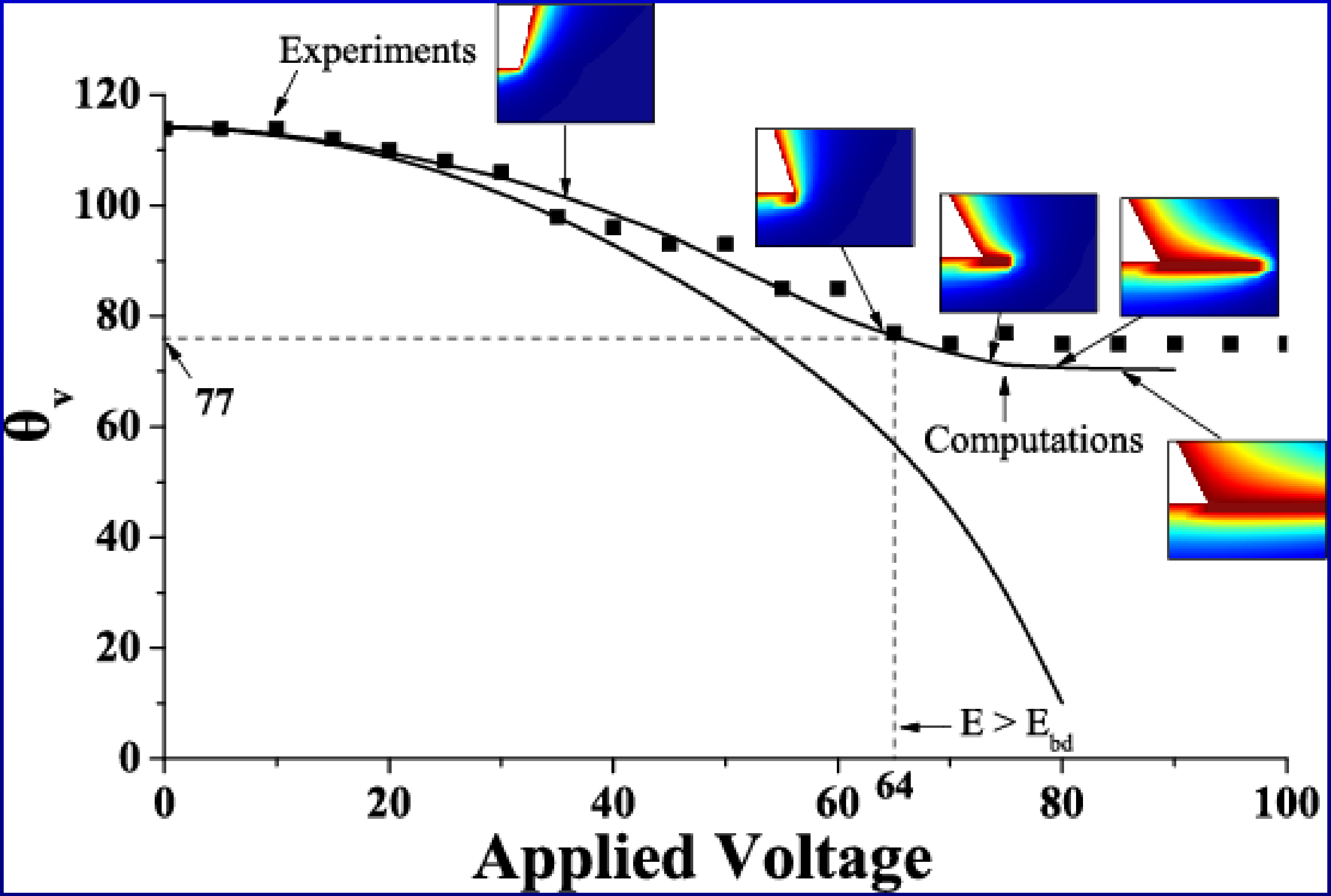
SIMULATING ELECTROWETTING BEYOND THE SATURATION



d =1000 nm, SiO_2, ε_r = 3.8, γ_{lv}=0.072 N/m, water, θ_Y = 117°

Drygiannakis, Papathanasiou & Boudouvis, *Langmuir* **25** (2009).

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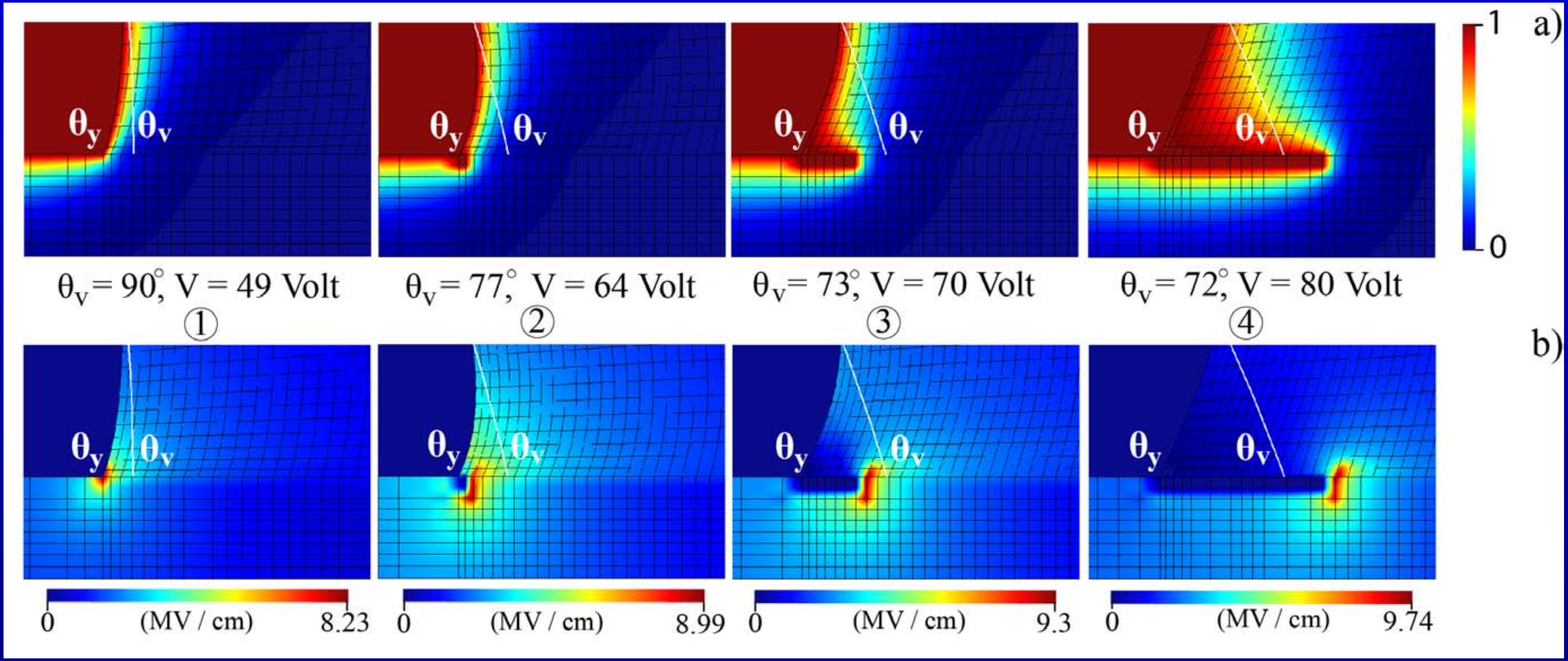
Potential and field strength distribution at the TPL



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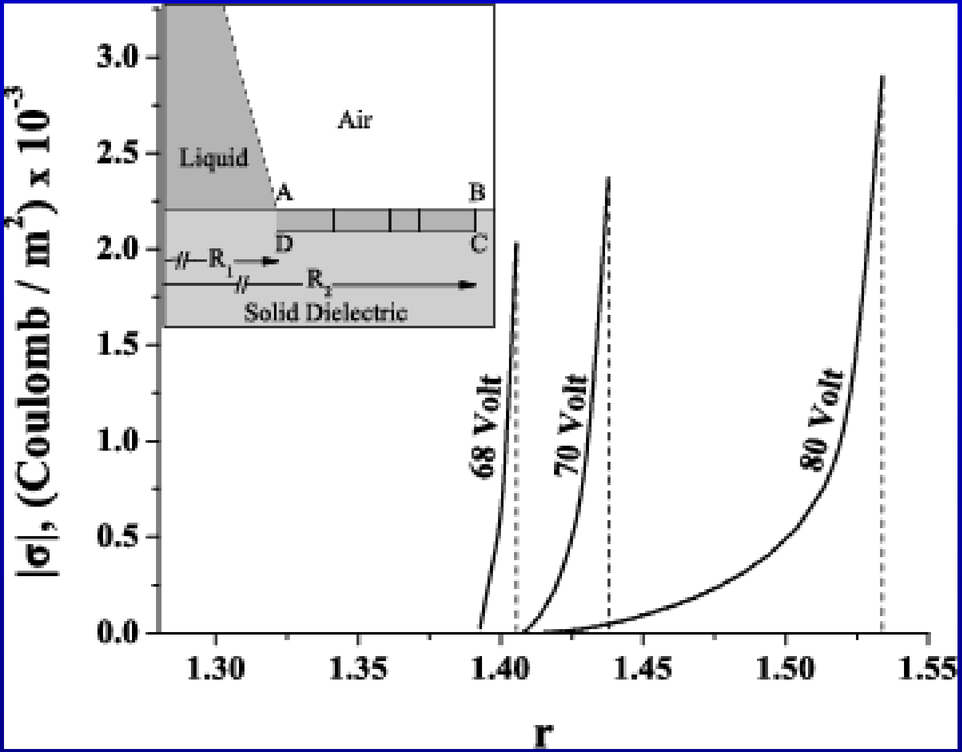
TRAPPED CHARGE DISTRIBUTION



d = 1 μm SiO_2, ε_r = 3.8

E_{bd}= 10 MV / cm

γ_{lv}=0.072 N/m, water

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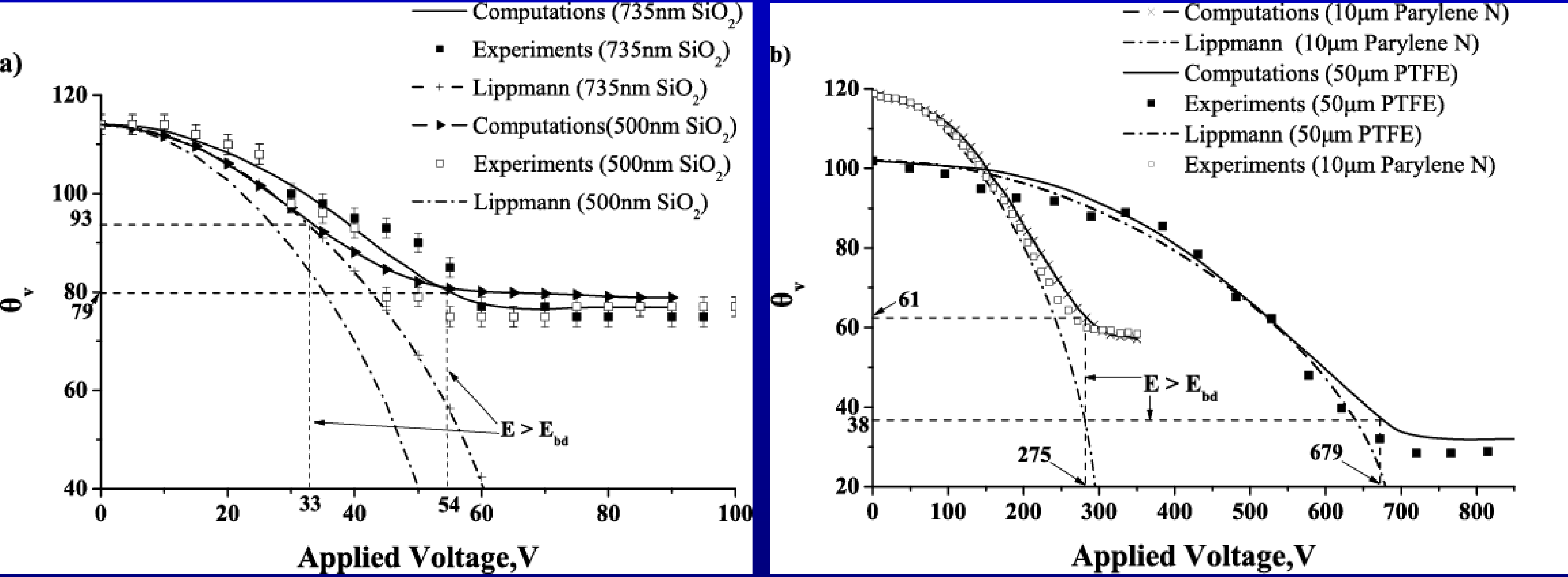
TESTING PREDICTIONS FOR DIFFERENT MATERIALS



Parylene and PTFE measurements from:
Verheijen & Prins, *Langmuir* **15**, 6616 (1999)
Vallet, Vallade & Berge, *European Physical Journal B* **11**, 583 (1999)

CONCLUSIONS

breakdown strength – charge trapping – contact angle saturation

- **succesfull simulation / prediction:**
  onset of the saturation
  asymptotic stabilization of the contact angle
  trapped charge (naturally computed)

  based only on material properties

- **the saturation is evidently shifted to higher voltages when composite dielectrics with higher breakdown strength are used**

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Collaborators / students

- Dr. Thanasis Papathanasiou
- Dr. Antonis Drygiannakis
- George Pashos, Doctoral student

FUNDING

- EU - European Social Fund
- Greek Ministry of Development - GSRT
- European Research Council