2037-13

Introduction to Optofluidics

1 - 5 June 2009

Optical control of electroosmotic fluid flow

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Optical control of electro-osmotic flow

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Concept for optical control of fluidics

- Aim: microfluidics system with total optical control

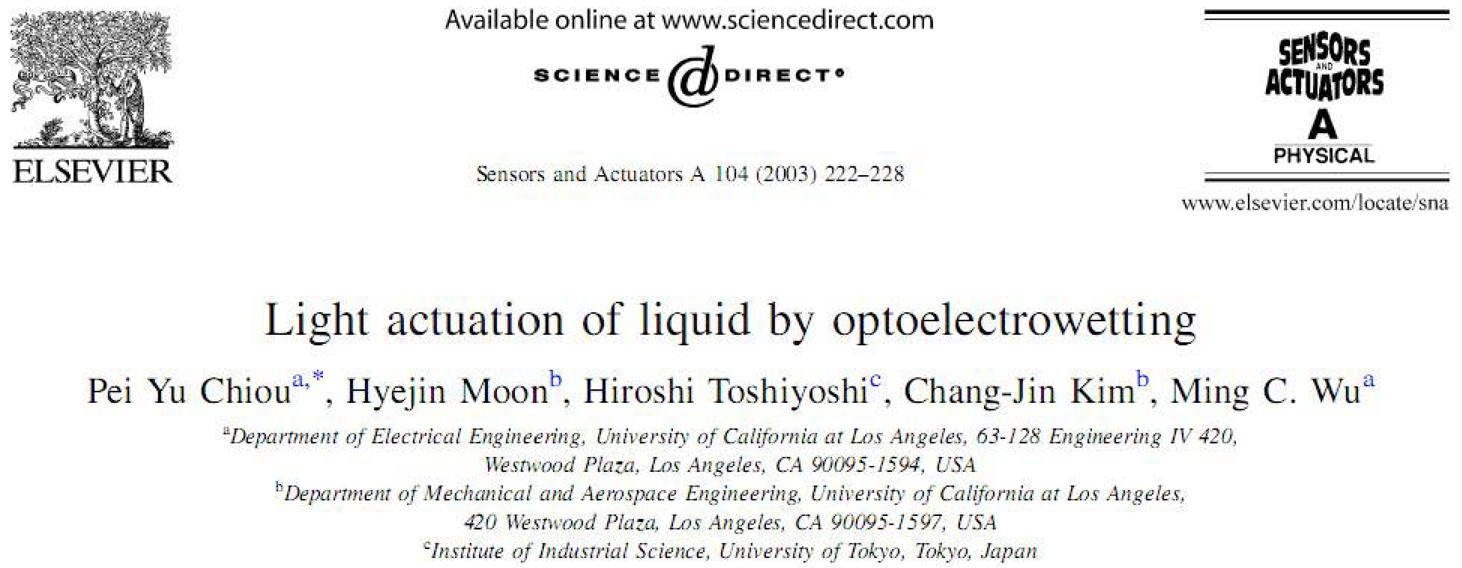
- Full photonic drive of microfluidic functions (pumping, steering, etc.) may not be optimal (not enough power)

Control flow by light, but drive electrically

Electro-osmosis controlled by light

Other approaches to eletrooptical fluid manipulation

electrowetting



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Light actuation of liquid by optoelectrowetting

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[c] *Institute of Industrial Science, University of Tokyo, Tokyo, Japan*

Other approaches to eletrooptical fluid manipulation

electrowetting

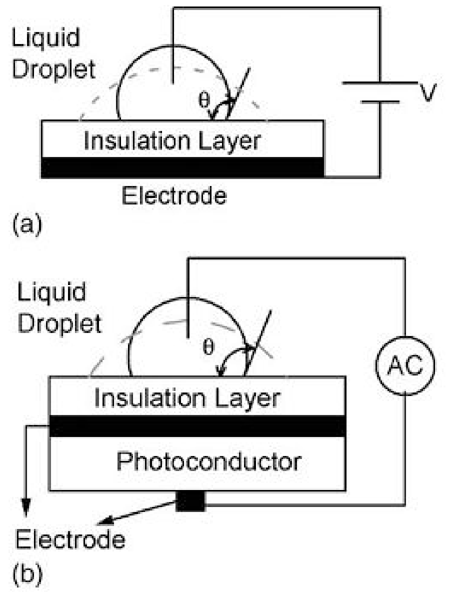


Fig. 1. (a) Conventional electrowetting under dc bias; and (b) optoelectrowetting with an integrated photoconductor under ac bias.

Other approaches to eletrooptical fluid manipulation

electrowetting

The voltage dependence of the contact angle, θ(V),

$$\cos[\theta(V_A)] = \cos[\theta(0)] + \frac{1}{2}\frac{\varepsilon}{d\gamma_{LV}}{V_A}^2$$

Other approaches to eletrooptical fluid manipulation

electrowetting

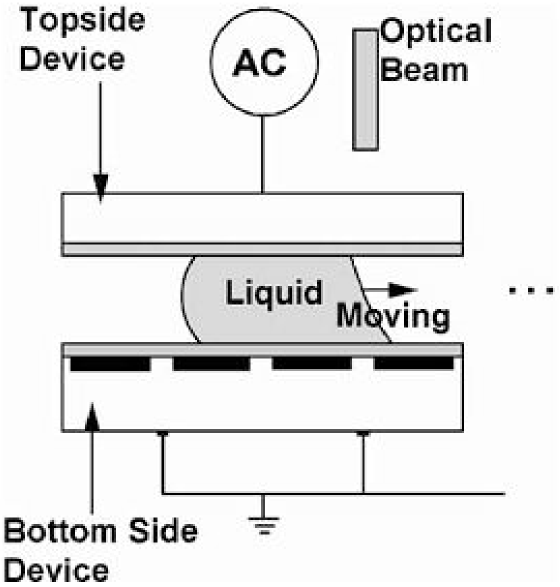
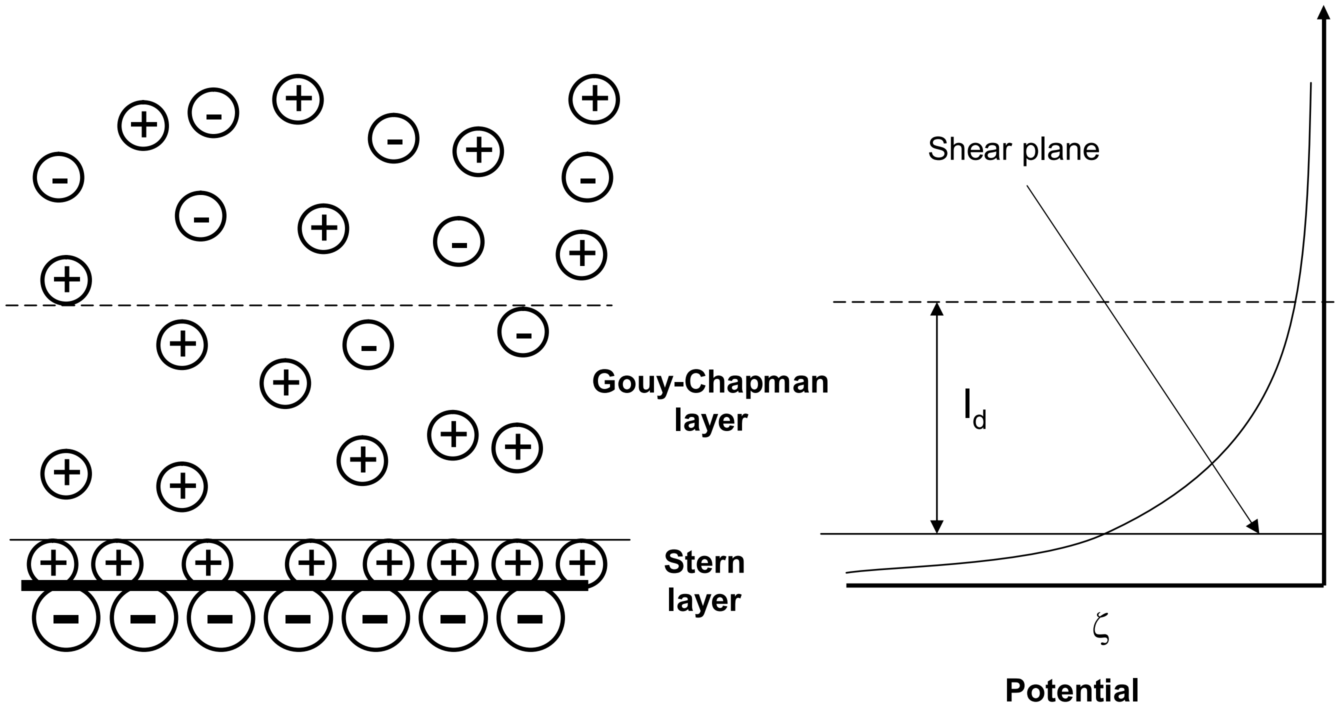


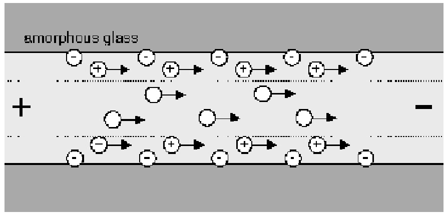
Fig. 3. Principle illustrating light actuation of liquid droplets.

Electro-osmosis



Electro-osmosis

The mechanism



www.unige.ch/cyberdocuments/unine/theses2000/GuenatO/these_body.html

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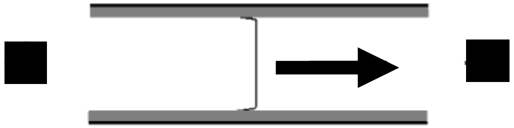
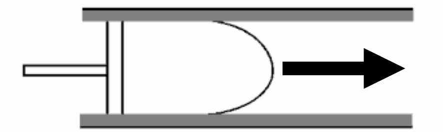
Velocity profile



Electro osmotic flow



Pressure driven flow

„Plug flow” (in the absence of back pressure)

”

n

Electro-osmosis basics

Boltzmann distribution i, c_i :

$$c_i(y) = c_{\infty,i}\exp(-\frac{ye\phi(y)}{kT})$$

C_i: concentration of ith ion, ϕ: local potential, y: distance from wall,

Net charge density in the EDL:

$$\rho_E = F\sum_{i=1}^{N} z_i c_i$$

Z: valence of ion, F: Faraday number

The relation of the net charge density and the local potential (Poisson equation):

$$\nabla^2\phi = \frac{-\rho_\varepsilon}{\varepsilon} \qquad (1)$$

ρ: net charge density, ε: permittivity

Combine these equations for the plane case:

$$\frac{d^2\phi}{dy^2} = \frac{-F}{\varepsilon}\sum_{i=1}^{N} z_i c_{\infty,i}\exp(-\frac{ze\phi(y)}{kT})$$

Electro-osmosis basics

With symmetric monovalent electrolyte this becomes:

$$\frac{d^2\phi}{dy^2} = \frac{2Fz_i c_\infty}{\varepsilon}\sinh(\frac{ze\phi(y)}{kT})$$

Poisson-Boltzmann equation

If kT>>zeϕ (Debye-Hückel limit)

$$\frac{d^2\phi}{dy^2} = \frac{\phi(y)}{\lambda_D^2}$$

where

$$\lambda_D = (\frac{\varepsilon kT}{2z^2F^2c_\infty})$$

: Debye length

For 10 mM concentration λ~ few nanometers

Electro-osmosis basics

Electro osmotic flow

Applied electric field introduces a Lorentz body force: $\rho b = \rho_E E$

The equation of motion for steady flow in the channel: $\nabla p = \mu \nabla^2 u + \rho_E E$

Substitute the Poisson equation (1): $\nabla^2 (u - \frac{\varepsilon E}{\mu} \phi) = \frac{\nabla p}{\mu}$

This equation is linear, so electric field and pressure driven flow can be separated

$$\nabla^2 (u_{EOF} - \frac{\varepsilon E}{\mu} \phi) = 0$$

$$\nabla^2 u_{pressure} = \frac{\nabla p}{\mu}$$

Continuity equation: $\frac{\partial u}{\partial x} = 0$

Electro-osmosis basics

Electro osmotic flow

Reasonable case: long, straight channel with uniform electric field

$$u_{EOF} - \frac{\varepsilon E}{\mu}\phi = \frac{-\varepsilon E \zeta}{\mu}$$

or

$$u_{EOF}(y,z) = \frac{-\varepsilon E \zeta}{\mu}(1 - \frac{\phi(y,z)}{\zeta})$$

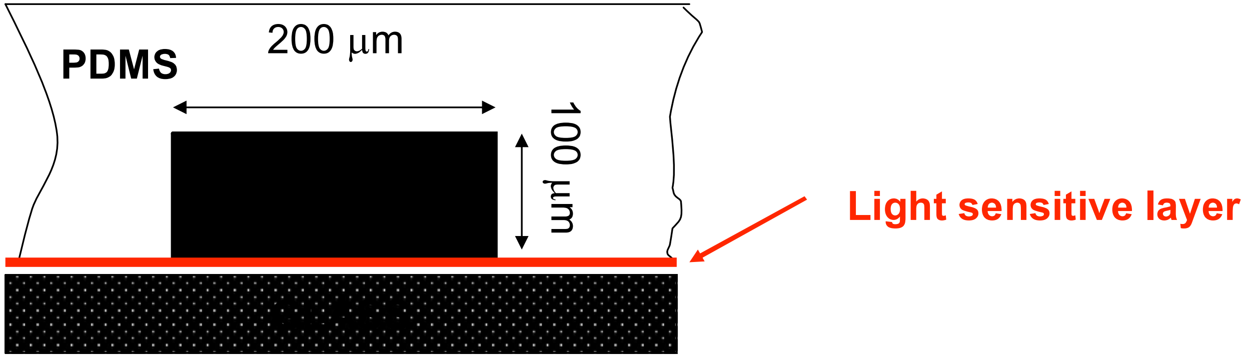
Photo electro-osmosis

- Parameters that determine flow:
  - Zeta potential
  - Electric field

- Modify Zeta potential, or
- Modify electric field **by light**

→ **Modify flow**

Basic experiment

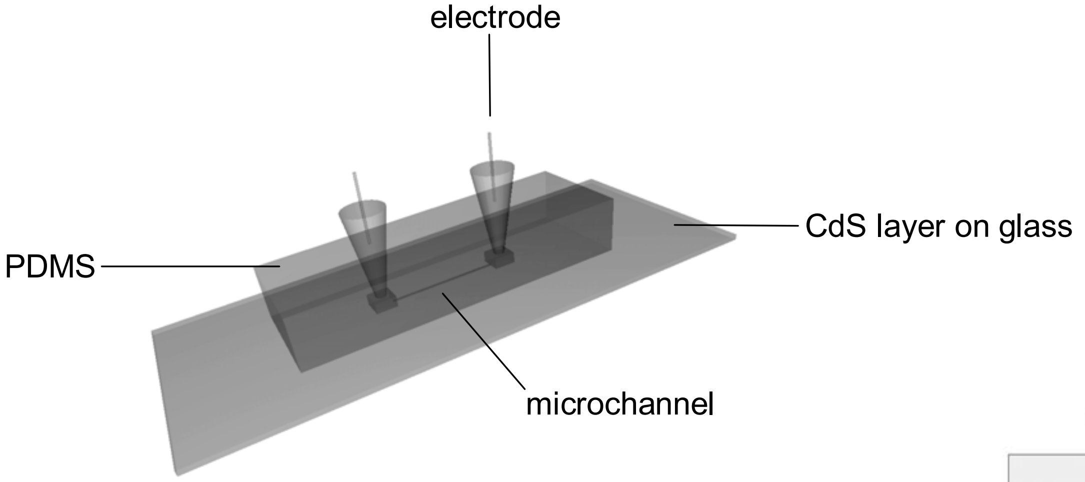


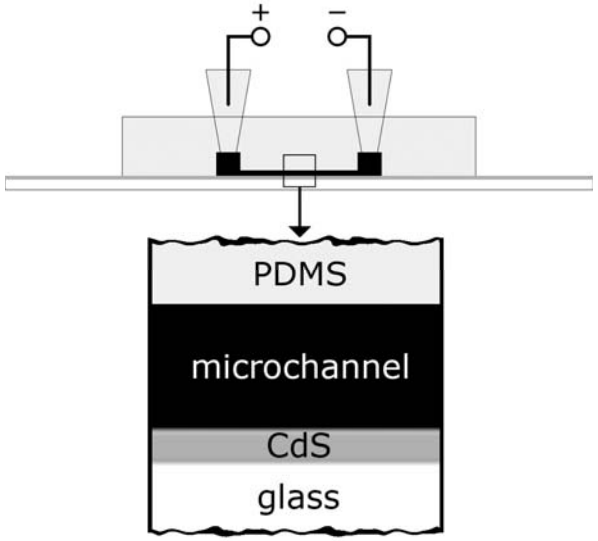
Photosensitive materials tested

- Change of surface charge
  - TiO_2
  - Bacteriorhodopsin
  - BSO
- Photoresistor
  - Amorphous Si
  - CdS

Experiments with CdS are shown

The sample

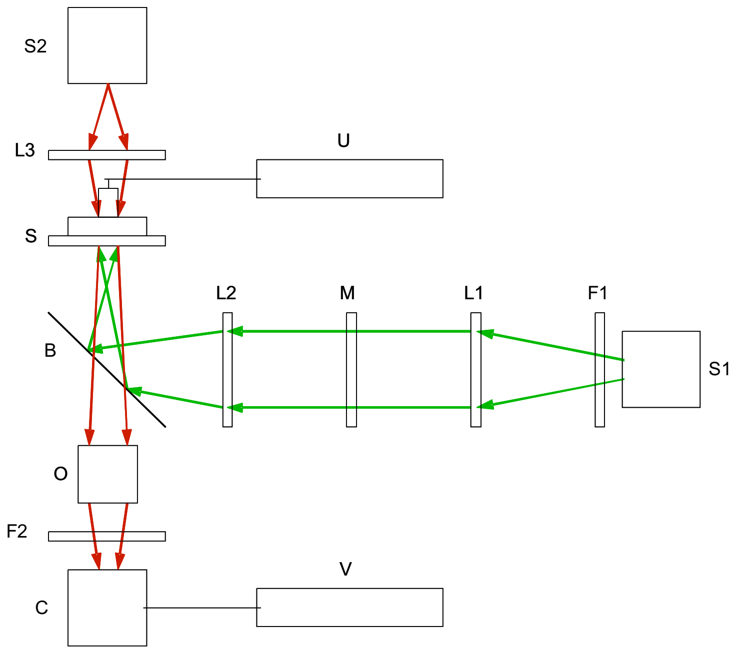




Sizes:

microchannel	200 μm x 100 μm x 10 mm
reservoirs	3 mm x 3 mm x 3 mm
CdS layer	200 nm

Experimental layout

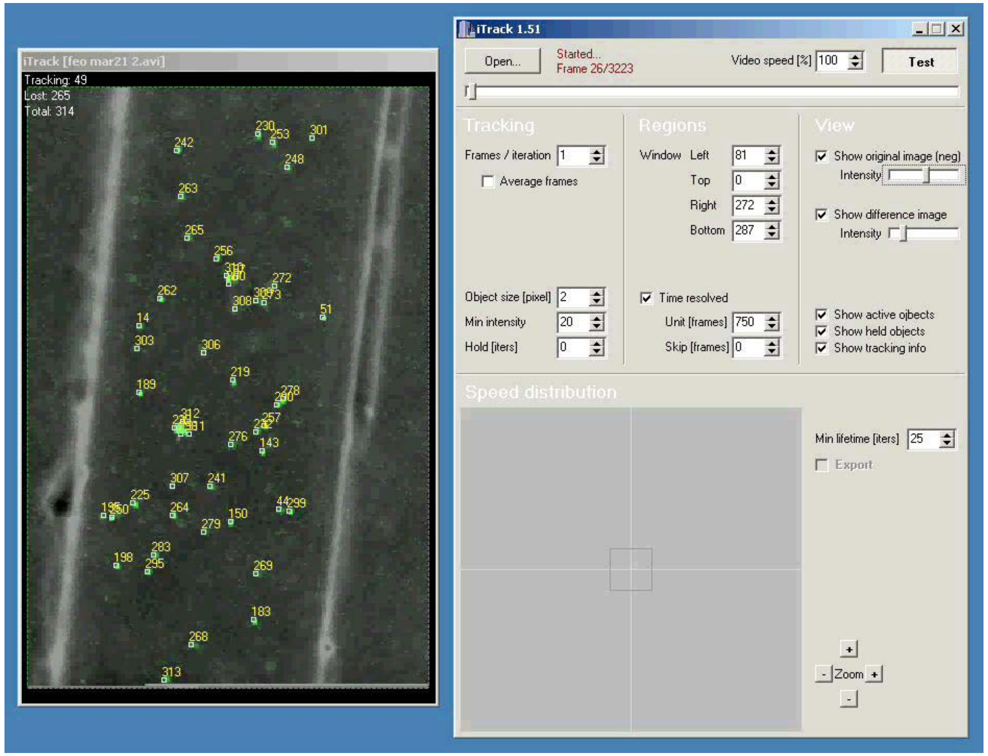


S: microfluidic sample, S1: mercury lamp, S2: LED, F1,F2: optical filters, L1,L2,L3: lenses, M: photomask, B: beam-splitter, O: objective, C: camera, V: video recorder, U: voltage source

The experiment

Oroszi et al. , Appl. Phys. Lett. (2006)

Characterize fluid flow



iTrack [feo mar21 2.avi]

Tracking: 49
Lost: 265
Total: 314

iTrack 1.51

Started...
Frame 26/3223

Video speed [%] 100

Tracking

Frames / iteration 1
☐ Average frames
Object size [pixel] 2
Min intensity 20
Hold [iters] 0

Regions

Window Left 81
Top 0
Right 272
Bottom 287
☑ Time resolved
Unit [frames] 750
Skip [frames] 0

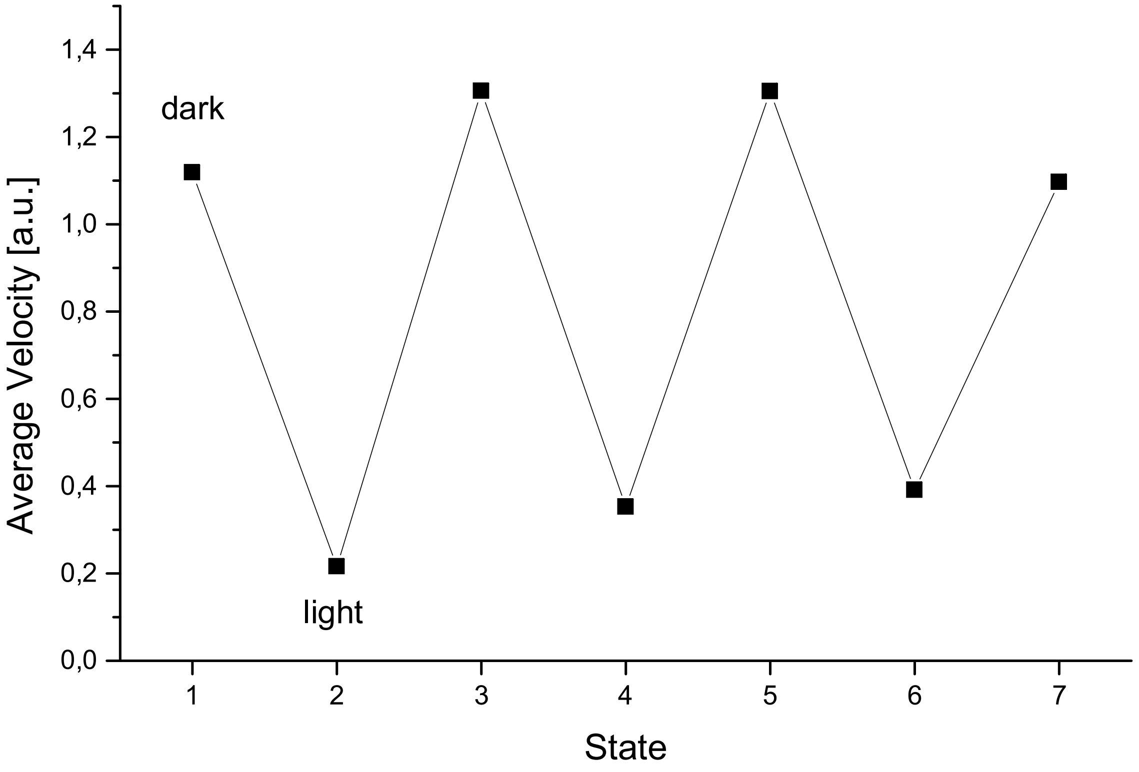
View

☑ Show original image (neg)
Intensity
☑ Show difference image
Intensity
☑ Show active ojbects
☑ Show held objects
☑ Show tracking info

Speed distribution

Min lifetime [iters] 25
☐ Export

Results


dark
light
Average Velocity [a.u.]
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
State
1
2
3
4
5
6
7

Modelling the experiments

- Simulation is done with FEMLAB (Comsol)
- Fluid is treated with the Navier-Stokes equation
- The electric field is calculated by electrostatics of conductive materials
- The effect of light is the decrease of the ohmic resistance upon illumination of one surface
- Electro-osmotic driving is treated with the Helmholz-Smoluchowski relation

Modelling the experiments

1. The structure of the electric field

The Maxwell equation in the absence of electric charges and external current:

$$-\nabla\sigma\nabla V = 0$$

V is the potential and σ is the conductivity as defined by

$$\vec{J} = \sigma\vec{E} = -\sigma\nabla V$$

Modelling the experiments

1. The structure of the electric field

The channel has three insulator and one conductive walls.

The conductivity values used were determined from experiments (for the conductive wall in dark and light)

Modelling the experiments

2. Modelling fluid flow

The Navier-Stokes equations for our stationary case:

$$-\eta\nabla^2\vec{v}+\rho\,\vec{v}\nabla\vec{v}+\nabla p=\vec{F}$$

$$\nabla\vec{v}=0$$

where ν is the velocity field of the fluid, ρ is the density, η is the dynamic viscosity, *p* is the pressure, and F is a volume force field

Modelling the experiments

3. Modelling osmotic flow

At the wall the velocity components perpendicular to the wall are set to zero, the two in-plane components are set according to the Helmholtz-Smoluchowski equation:

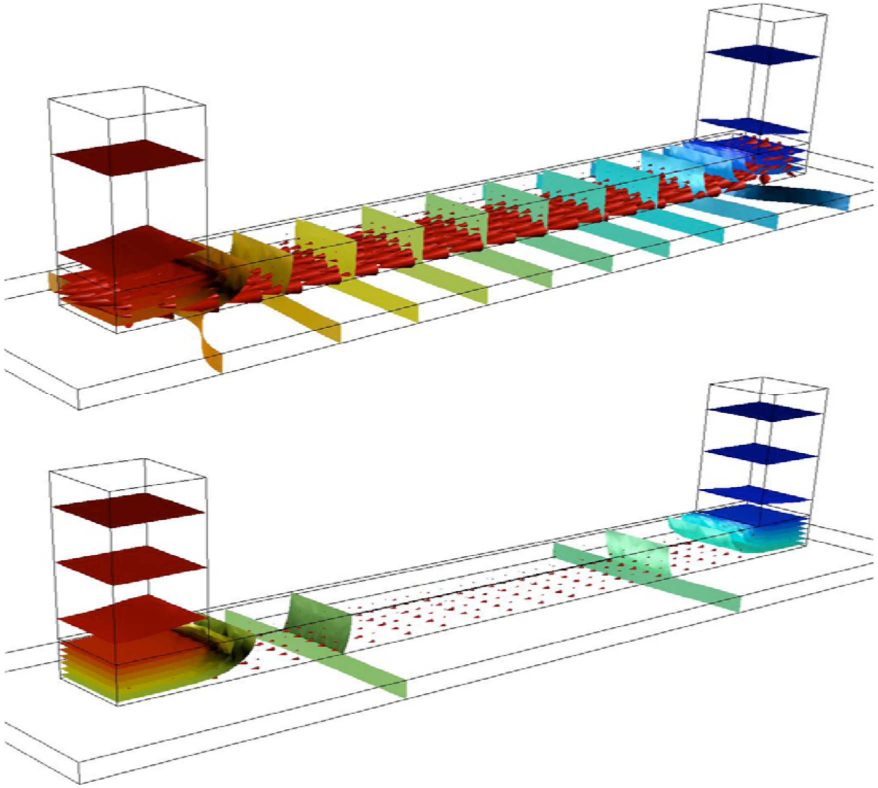
$$\bar{v} = \frac{\varepsilon_w \zeta_0}{\eta} \overline{E}$$

where E is the electric field, ζ is the zeta-potential at the wall and ε is the fluid’s absolute permittivity

Realistic values were given to the Zeta potential:

PDMS: -100 mV, CdS: -5 mV

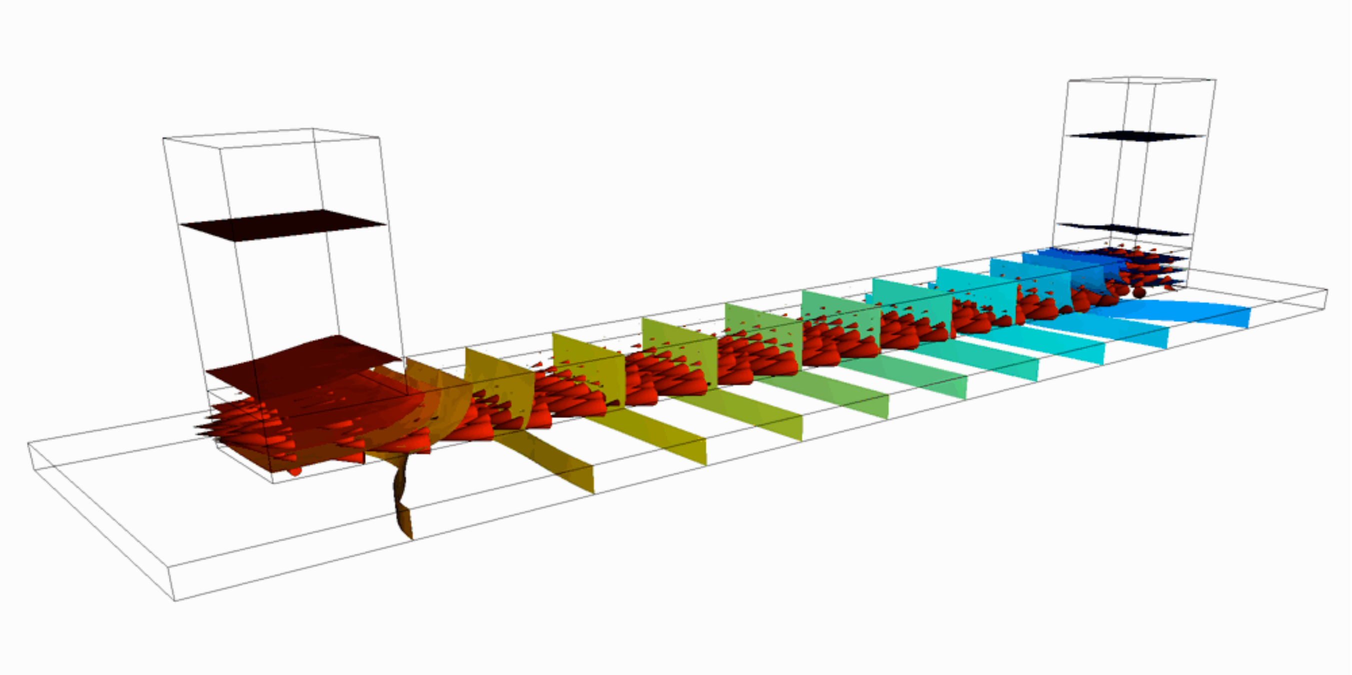
Simulation of electro-osmotic switching



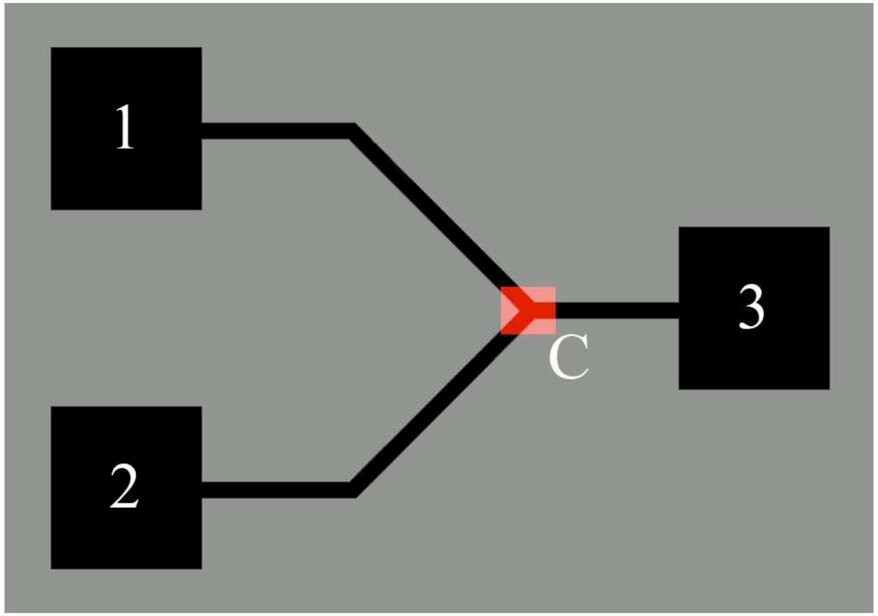
Dark

Light

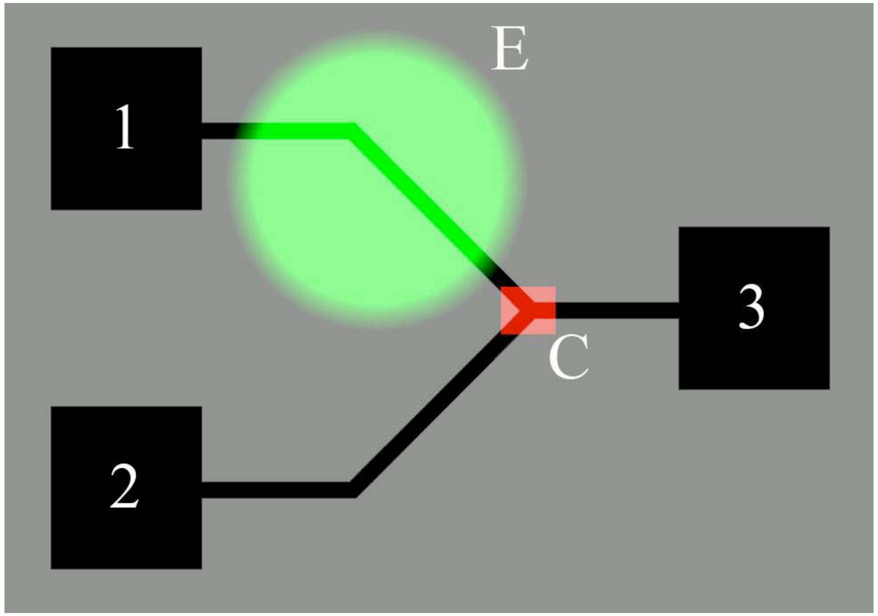
Simulation of electro-osmotic switching



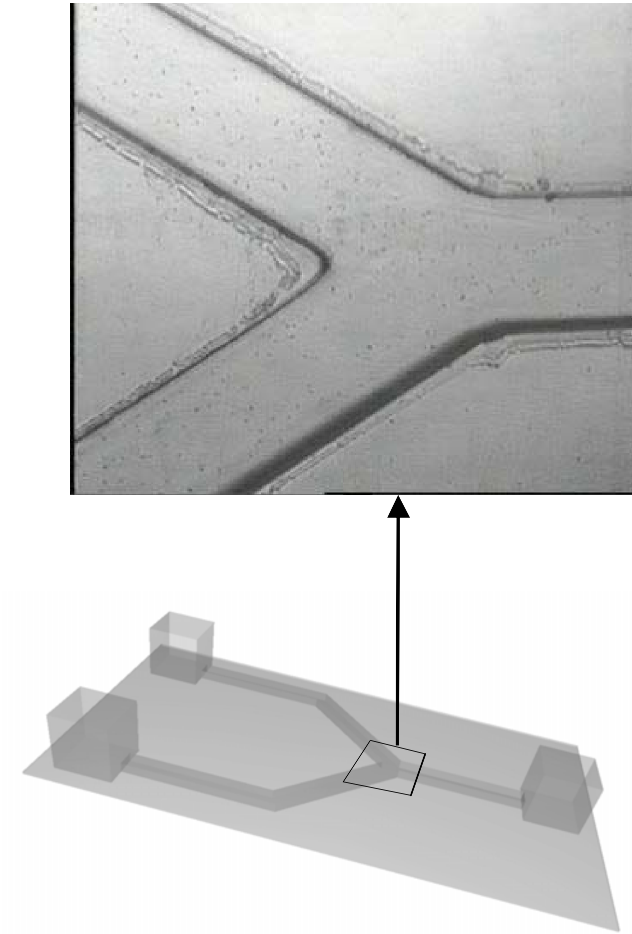
Fluid switch

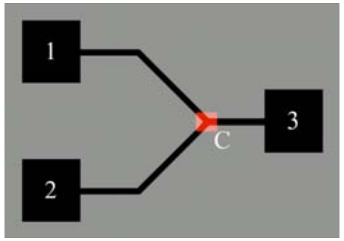


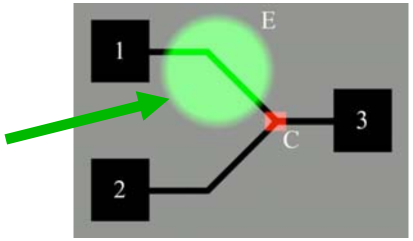
Fluid switch



Y-branch

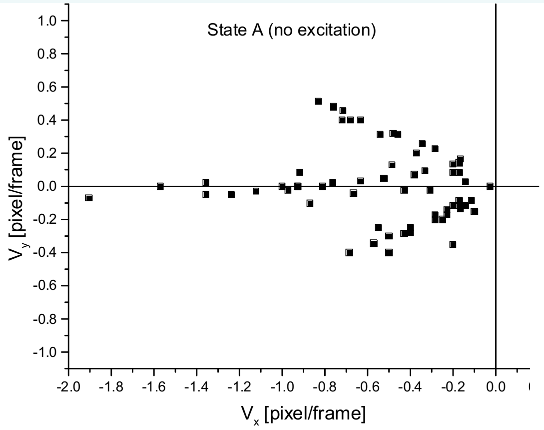


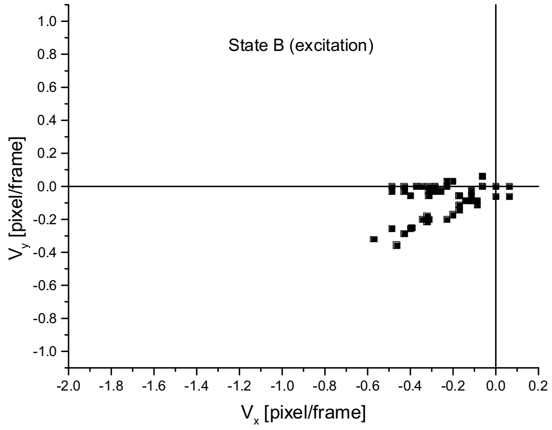


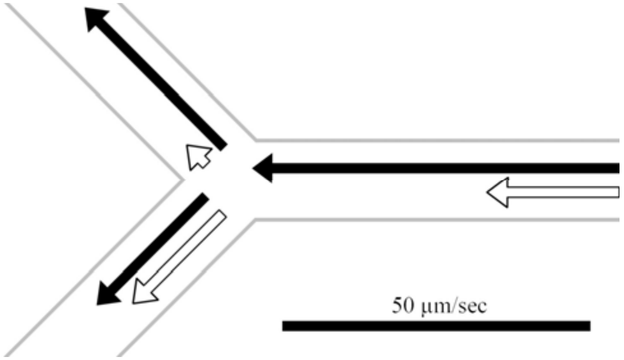


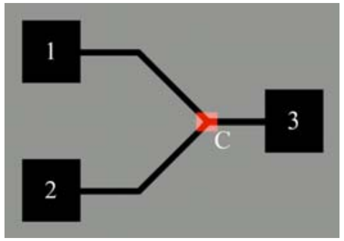
excitation

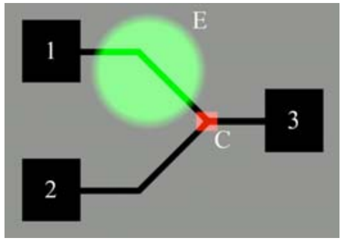
Y-branch – evaluation



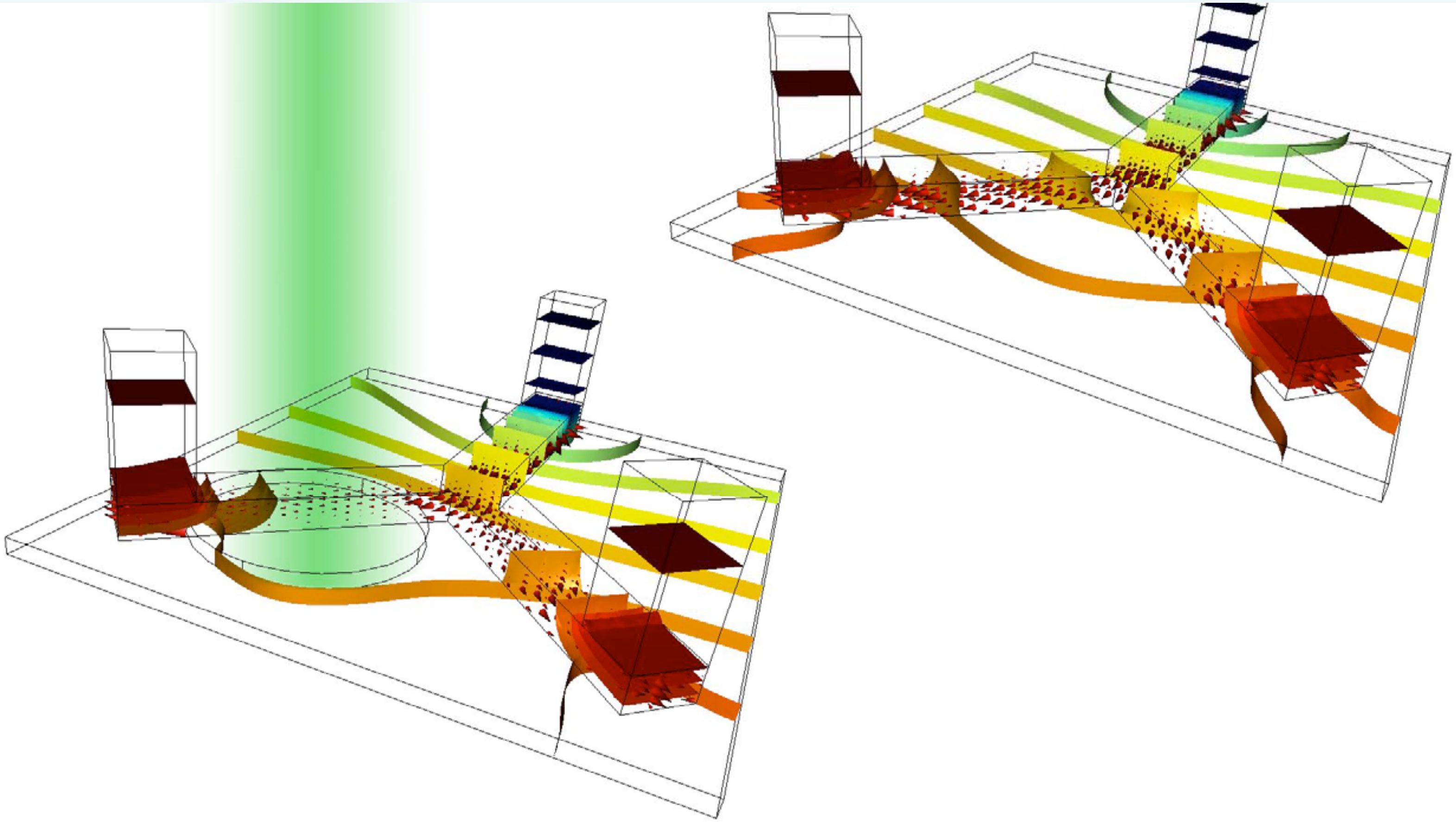






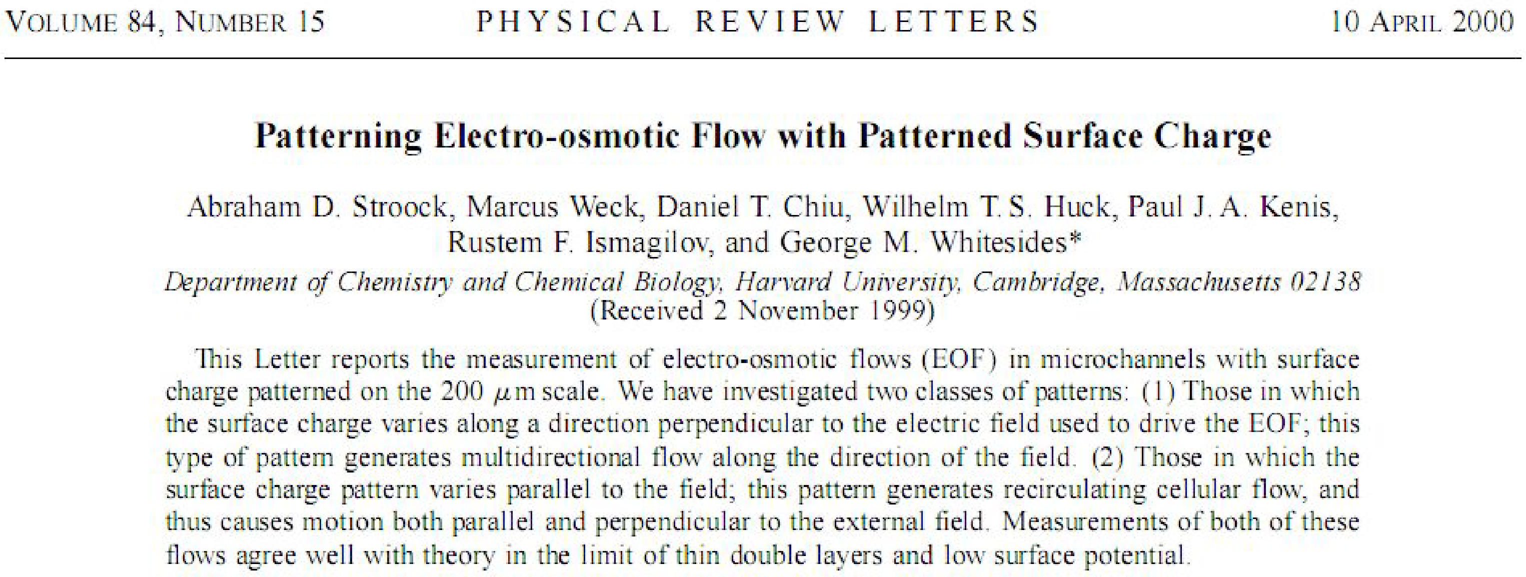


Y-branch – simulation



Oroszi et al., 2006, Appl.Phys.Lett.

Manipulation of flow pattern in an electro-osmotic system



VOLUME 84, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 2000

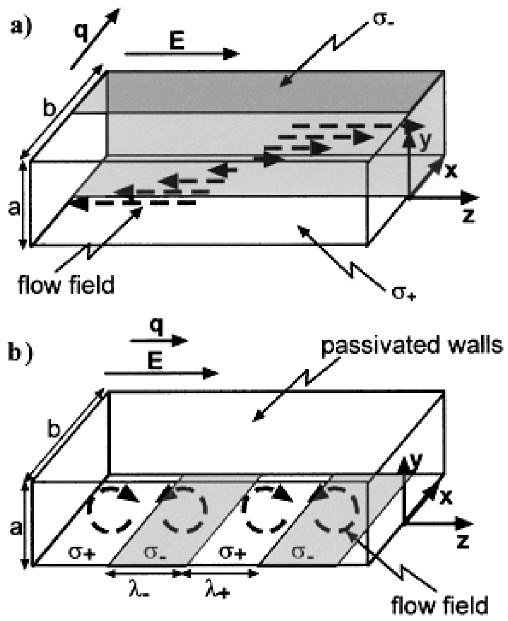
Patterning Electro-osmotic Flow with Patterned Surface Charge

Abraham D. Stroock, Marcus Weck, Daniel T. Chiu, Wilhelm T. S. Huck, Paul J. A. Kenis,
Rustem F. Ismagilov, and George M. Whitesides*
Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138

(Received 2 November 1999)

This Letter reports the measurement of electro-osmotic flows (EOF) in microchannels with surface charge patterned on the 200 μm scale. We have investigated two classes of patterns: (1) Those in which the surface charge varies along a direction perpendicular to the electric field used to drive the EOF; this type of pattern generates multidirectional flow along the direction of the field. (2) Those in which the surface charge pattern varies parallel to the field; this pattern generates recirculating cellular flow, and thus causes motion both parallel and perpendicular to the external field. Measurements of both of these flows agree well with theory in the limit of thin double layers and low surface potential.

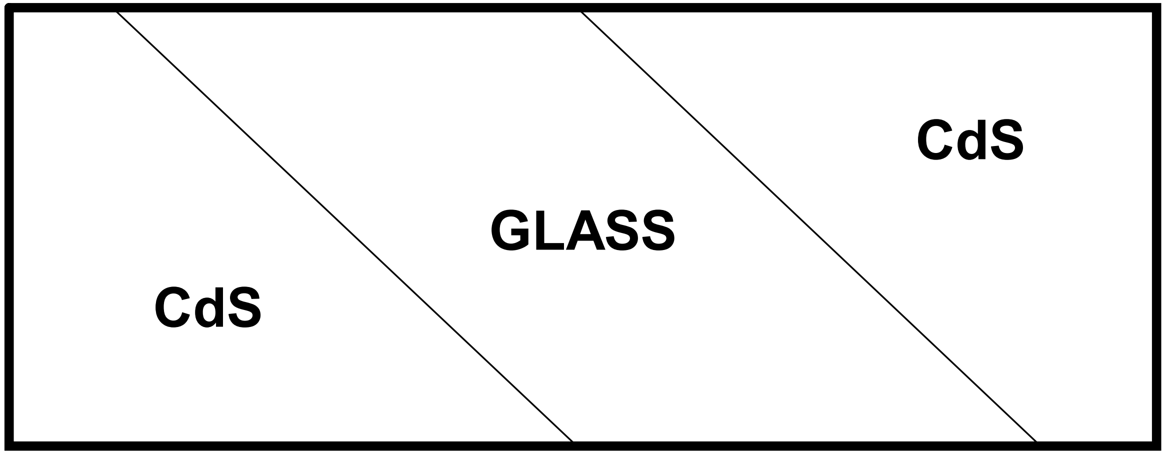
Manipulation of flow pattern in an electro-osmotic system



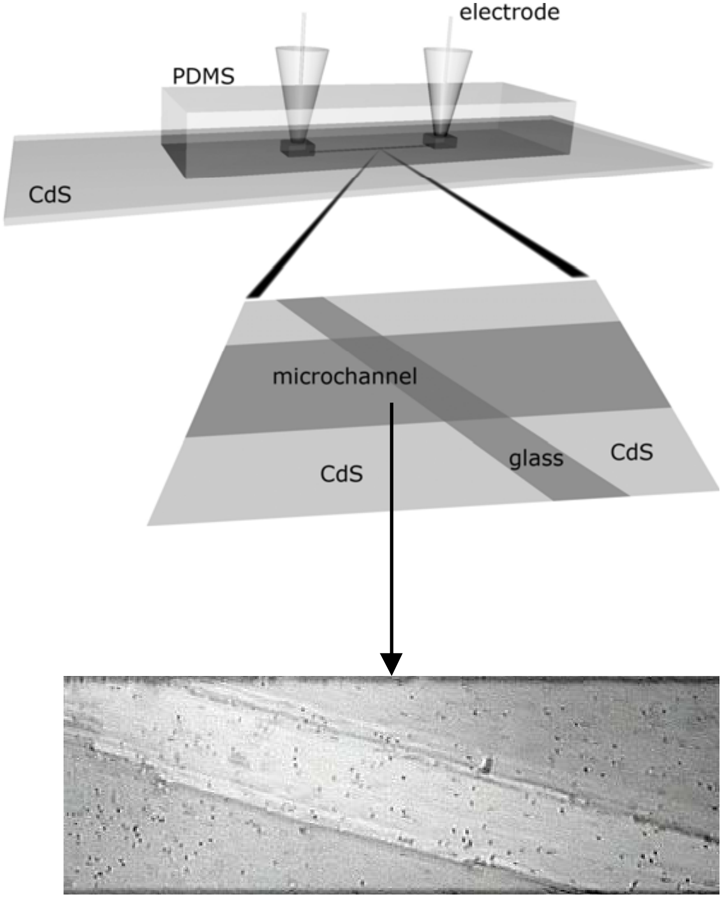
The driving field is patterned with patterned electrodes

Generate complex flow pattern by light

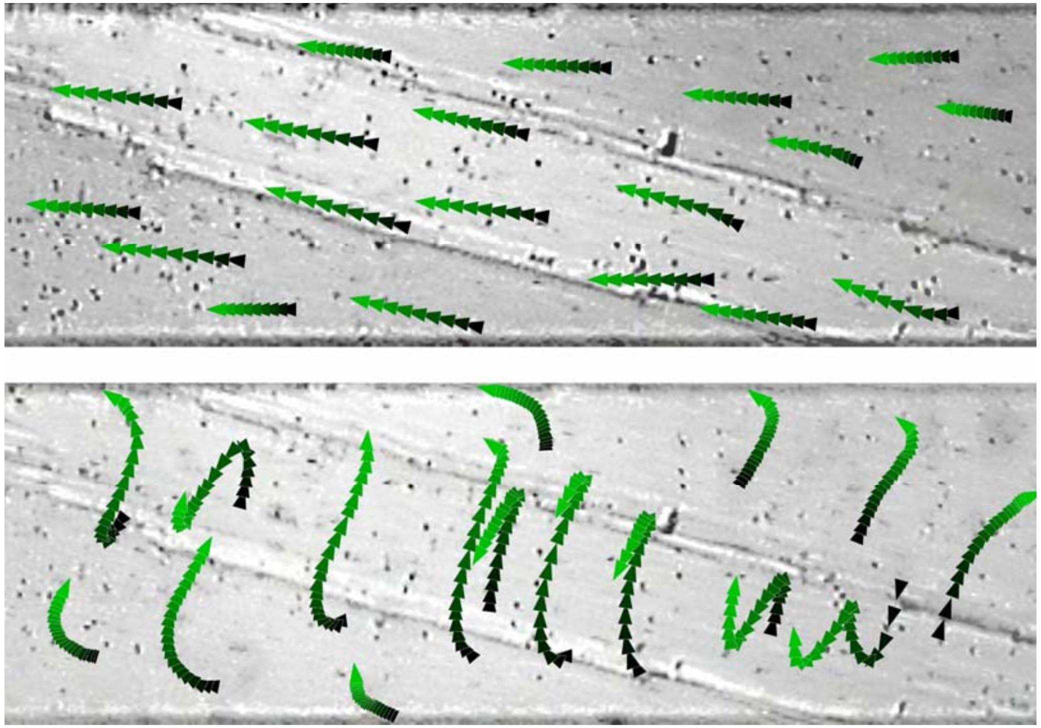
Surface of glass support



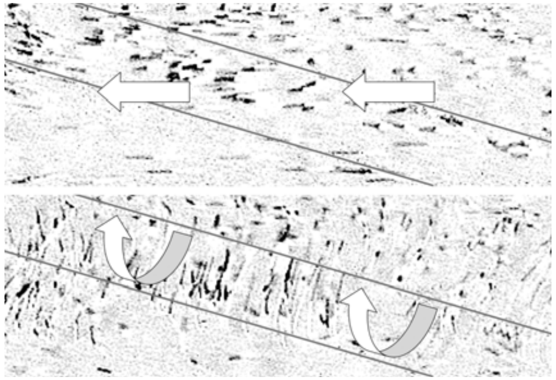
Helical modulation of fluid flow–sample and experiment

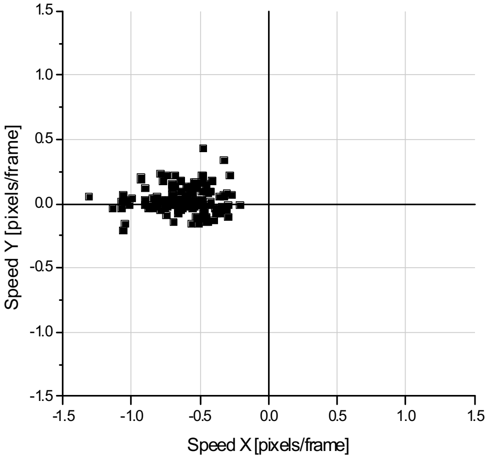


Visualization of flow

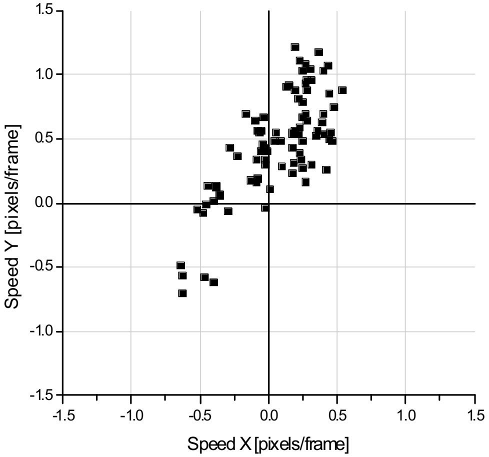


Helical modulation of fluid flow - evaluation



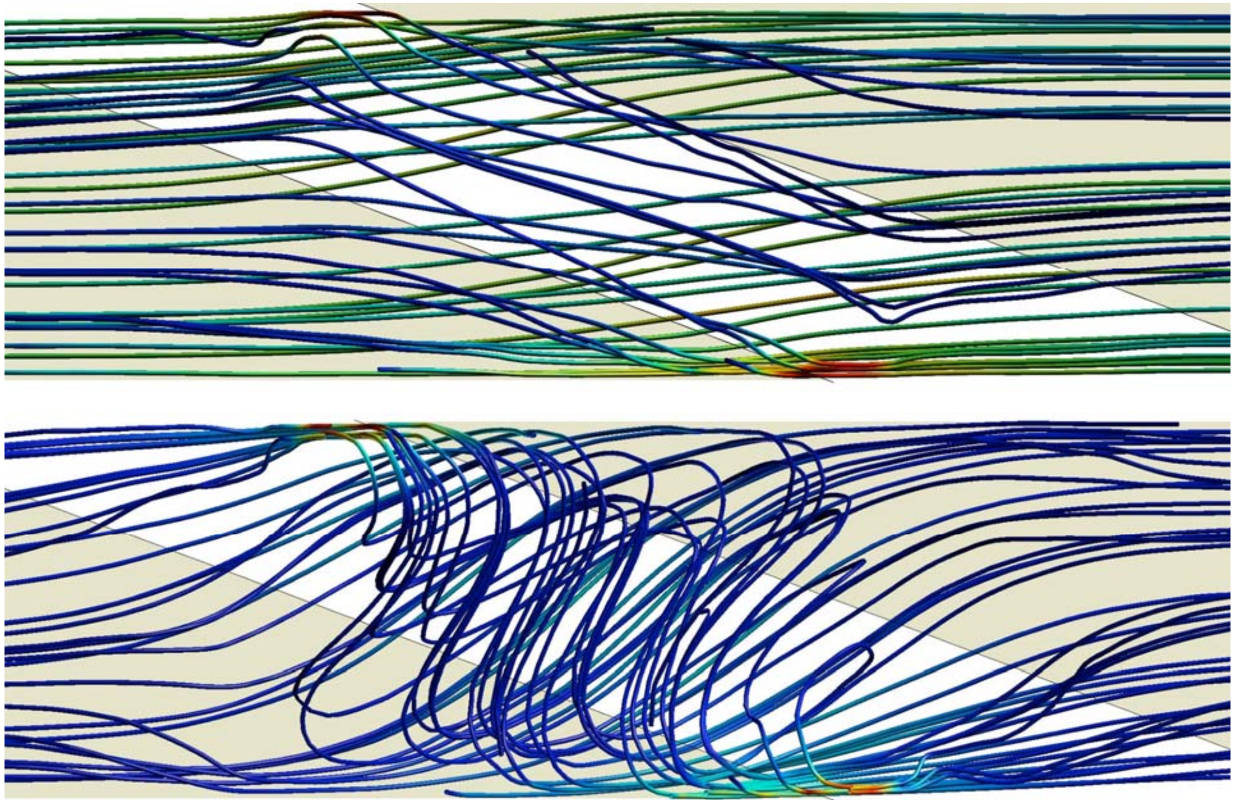


dark:

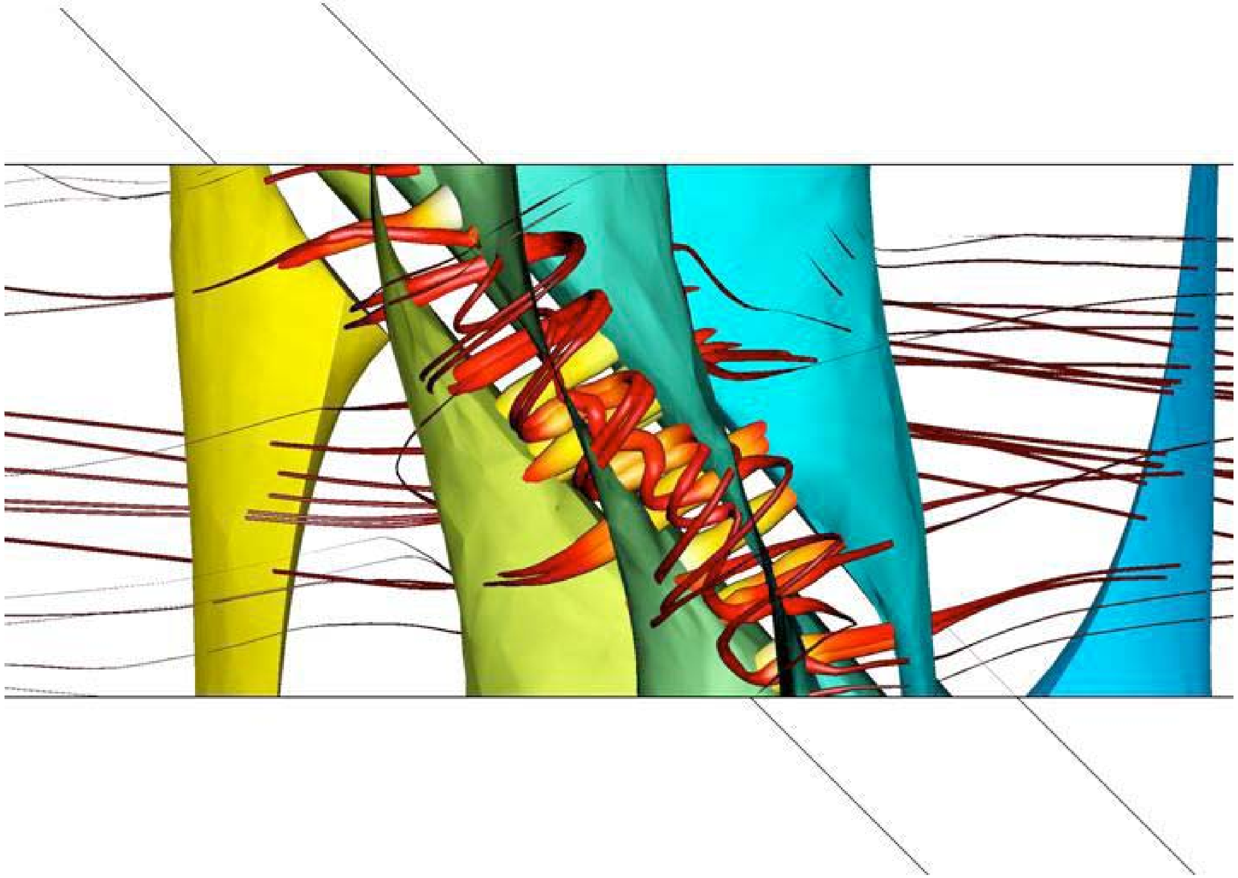


light:

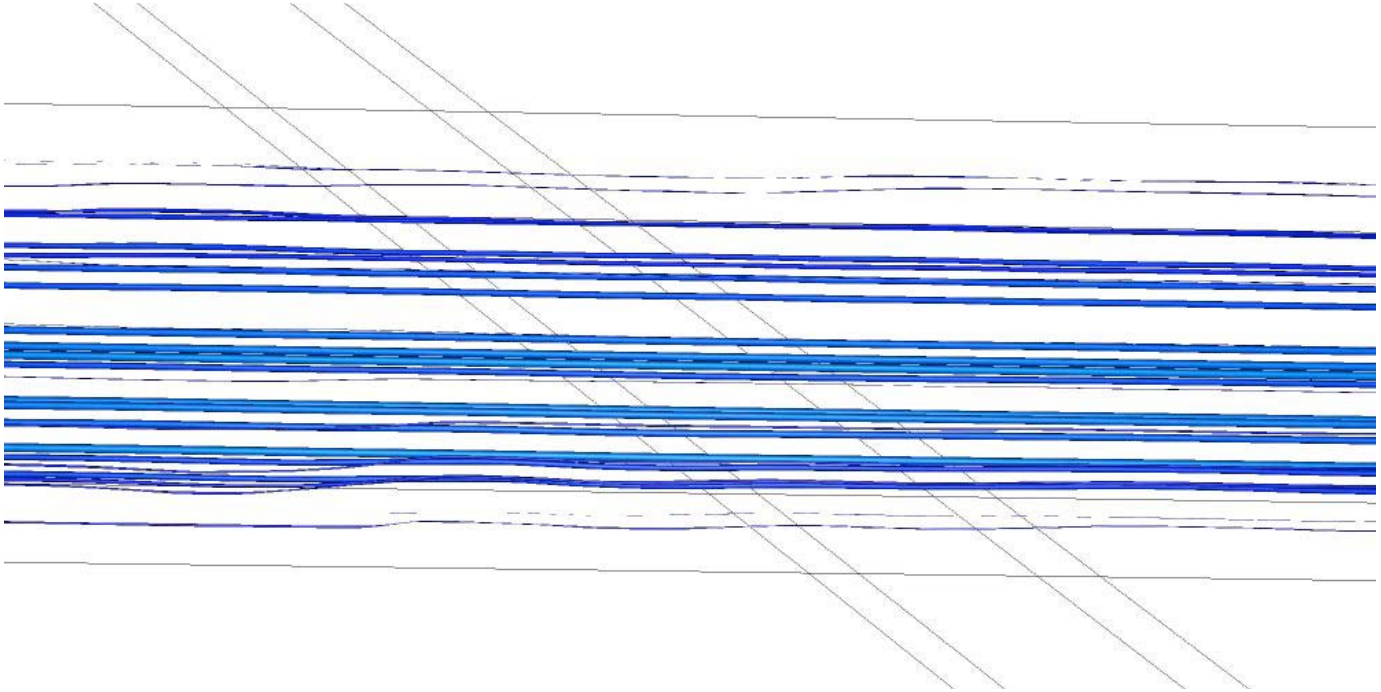
Simulation



Simulation

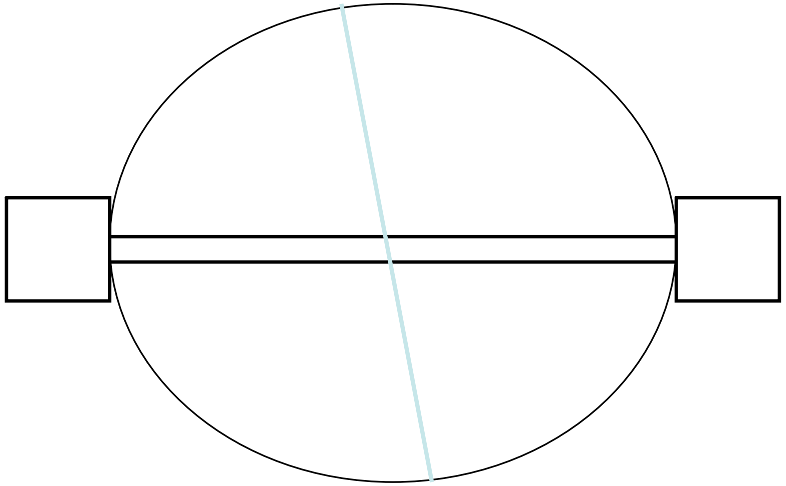


Simulation

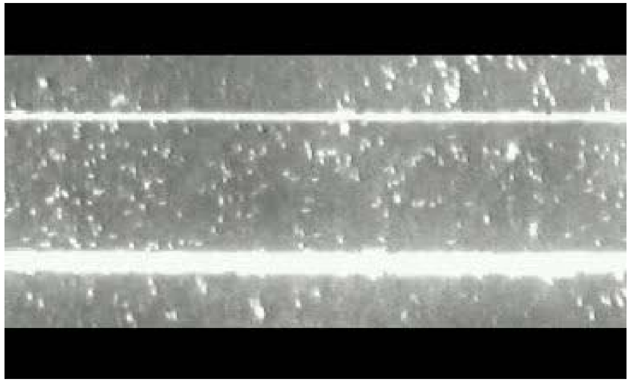


Oroszi et al., 2008, Nanofluidics, Microfluidics

Change flow pattern by projecting image on the photoconductor



Change flow pattern by projecting image on the photoconductor



Conclusions

- Optoelectroosmosis has promise in manipulationg local flows (mixing in reactors, etc.).

Other approaches to eletrooptical fluidic manipulation

2. Electro-optical trapping

Electrophoretic assembly of colloidal crystals with optically tunable micropatterns

R. C. Hayward, D. A. Saville & I. A. Aksay

Department of Chemical Engineering and Princeton Materials Institute,
Princeton University, Princeton, New Jersey 08544-5263, USA

NATURE | VOL 404 | 2 MARCH 2000 | www.nature.com

Other approaches to eletrooptical fluidic manipulation

2. Electro-optical trapping

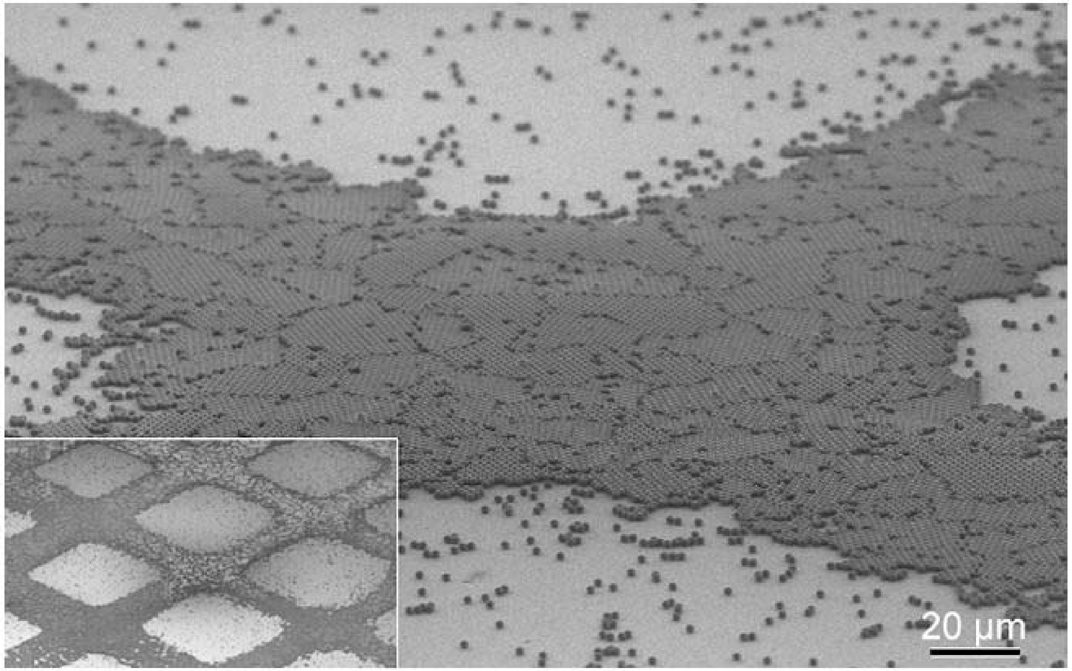
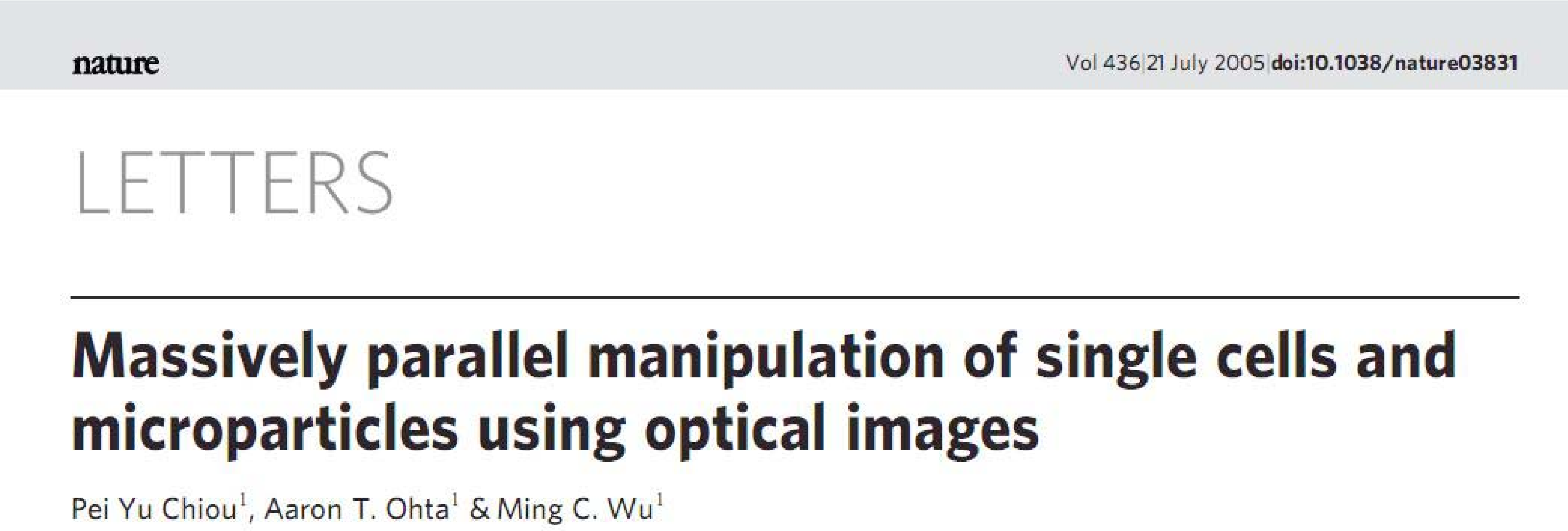


Figure 3 Scanning electron microscope image of a pattern produced by method B. Note that dense-packing of particles results in crystalline (ordered) domains that vary in size (10–20 μm). The inset (~600 μm wide) shows the overall appearance of the pattern. Some areas shown in the inset appear white due to particle charging in the SEM. Charging in these regions may result from the higher particle density which inhibits charge transfer from the uppermost particles to the conducting substrate.

Other approaches to eletrooptical fluidic manipulation

2. Electro-optical trapping



nature Vol 436|21 July 2005|doi:10.1038/nature03831

LETTERS

Massively parallel manipulation of single cells and microparticles using optical images

Pei Yu Chiou[1], Aaron T. Ohta[1] & Ming C. Wu[1]

Other approaches to eletrooptical fluidic manipulation

2. Electro-optical trapping

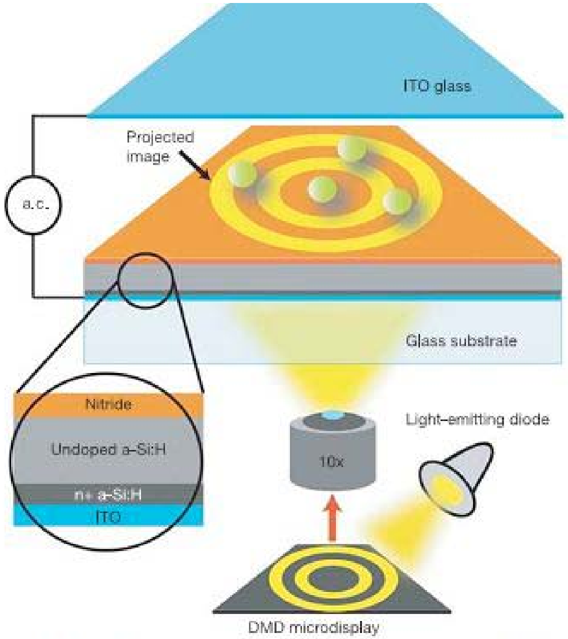


Figure 1 | Device structure used in optoelectronic tweezers. Liquid that contains microscopic particles is sandwiched between the top indium tin oxide (ITO) glass and the bottom photosensitive surface consisting of ITO-coated glass topped with multiple featureless layers: 50 nm of heavily doped hydrogenated amorphous silicon (a-Si:H), 1 μm of undoped a-Si:H, and 20 nm of silicon nitride. The top and bottom surfaces are biased with an a.c. electric signal. The illumination source is an light-emitting diode operating at a wavelength of 625 nm (Lumileds, Luxeon Star/O). The optical images shown on the digital micromirror display (DMD) are focused onto the photosensitive surface and create the non-uniform electric field for DEP manipulation.