DC and AC Electrokinetics

- Dielectrophoresis
- Electro-osmosis

References:

- Pohl, H.A., *Dielectrophoresis: The Behavior of Neutral Matter in Nonuniform Electric Fields* (Cambridge University Press, Cambridge, 1978).
- T. B. Jones, *Electromechanics of particles* (Cambridge University Press, Cambridge, 1995).
- Kirby, BJ, "Micro- and Nanoscale Fluid Mechanics: Transport in Microfluidic Devices," Cambridge University Press, 2010.

Dielectrophoresis (DC Field)

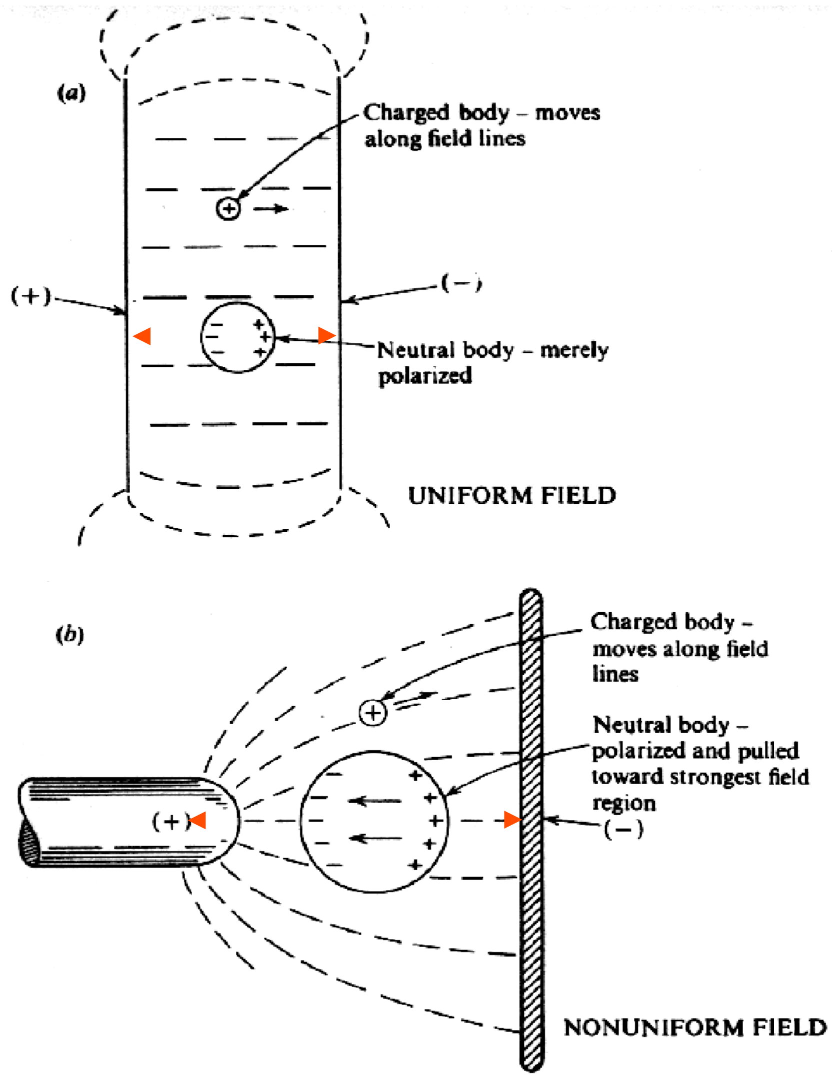


Fig. 2.1. Comparison of behaviors of neutral and charged bodies in (*a*) a uniform electric field; (*b*) a nonuniform electric field.

Uniform DC field:

Dielectric (neutral) object stays still

Non-uniform DC field:

Dielectric object moves

- towards high-field gradient region (+DEP)
- towards low-field gradient region (–DEP)

Pohl (1978)

Dielectrophoresis (AC Field)

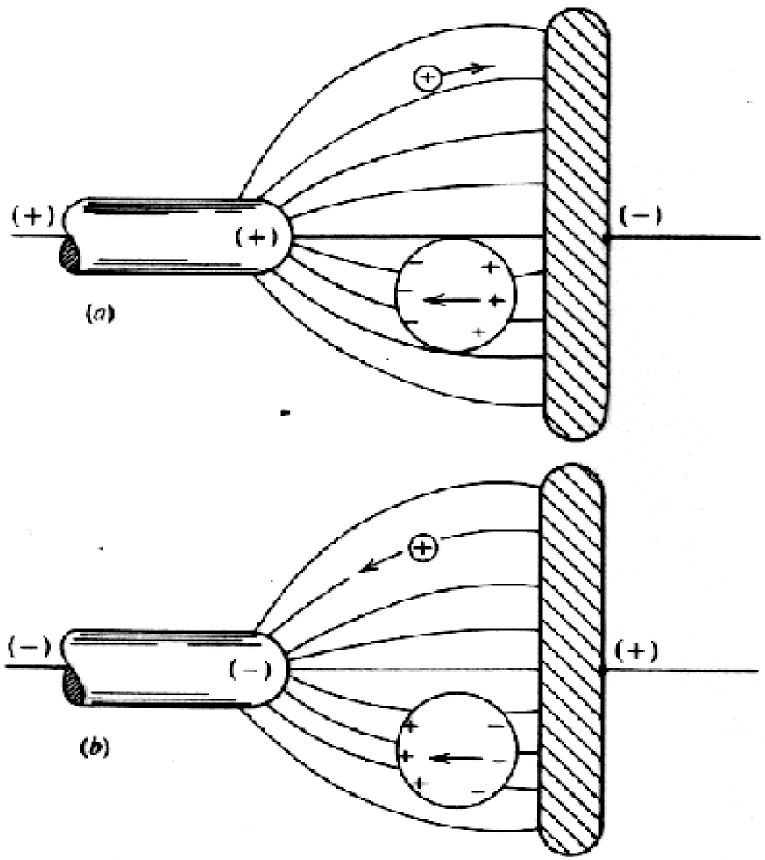


Fig. 2.2. Comparison of behaviors of neutral and charged bodies in an alternating nonuniform electric field.

Pohl (1978)

In Non-uniform AC Field:

Charged body displays no net displacement

Neutral body (dielectric) object moves

- towards high-field gradient region (+DEP) → trapping!
- towards low-field gradient region (−DEP) → repelling!

Dielectrophoresis (DEP)

The classical DEP theory states that the dielectrophoretic force arises from the interaction of the induced dipole of a polarizable object and an external non-uniform electric field (Pohl 1978).

DEP is a technique which can be used to separate cells or molecules based on the difference in their polarizability.

Potential energy of a dielectric object in an electric field:

$$U = -\mathbf{p}\cdot\mathbf{E} = -\alpha V E^2$$

Dielectrophoretic force:

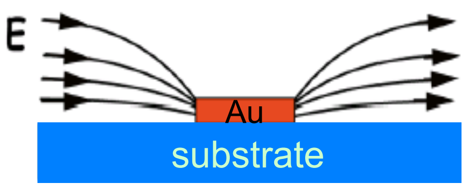
$$F = -\nabla U \sim E(dE/dy)$$

$$F = 2\pi a^3 \varepsilon_m \operatorname{Re}\left(\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right)\nabla(E^2)$$

Clausius-Mossotti factor

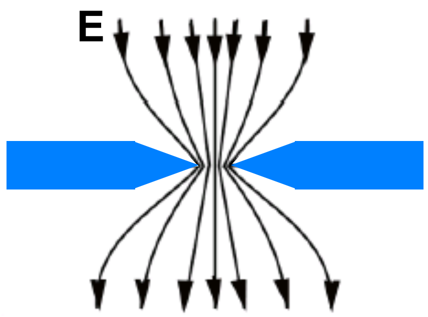
Sphere of radius a, ε_m = 80 for water

a. Metallic trap



(Side view)

b. Electrodeless trap (EDEP)



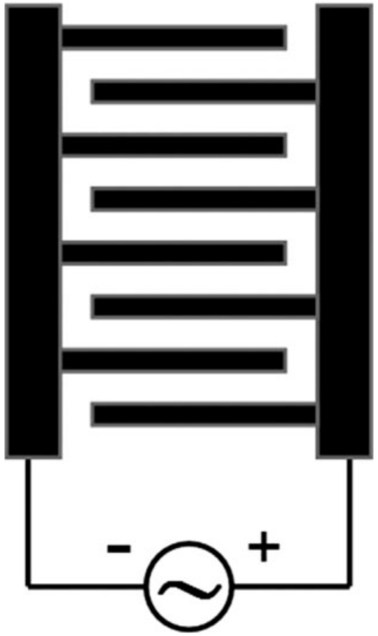
(top view)

Application of DEP in Biology and …

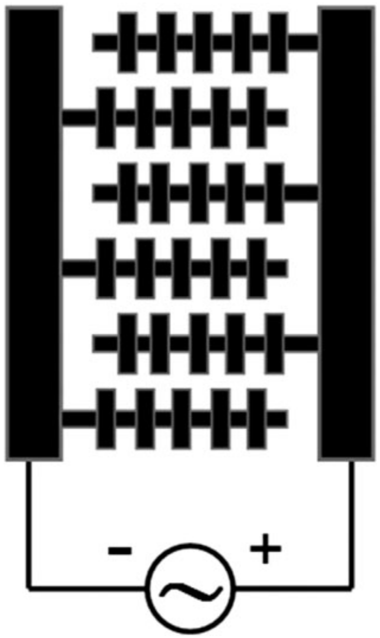
- **Cells**
  - ❖ Separation of yeast (Pethig et al, 1994)
  - ❖ Cell fission of sea urchin eggs (Marszalek & Tsong, 1995)
  - ❖ Cell fussion (Matsuda et al., 1979)
- **Viruses**
  - ❖ Separation of tobacco mosaic virus and herpes simplex virus (Morgan et al, 1999)
- **DNA**
  - ❖ Increase resolution of DNA fractionatoin or sequencing
  - ❖ Enhance in-situ hybridization
- **Protein**
  - ❖ Protein capture/preconcentration
- **Latex beads**
  - ❖ DEP ratchet (Silberzan et al, 1998)

Typical electrode geometries for MDEP

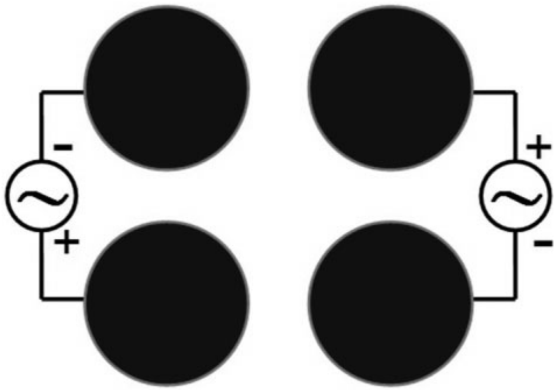
2-D simple gap electrodes



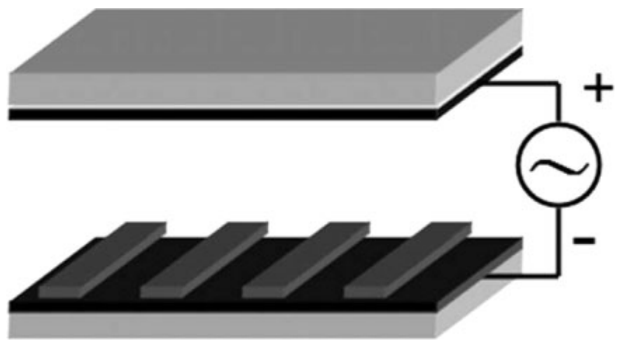
2-D interdigital electrodes



2-D quadruple electrodes

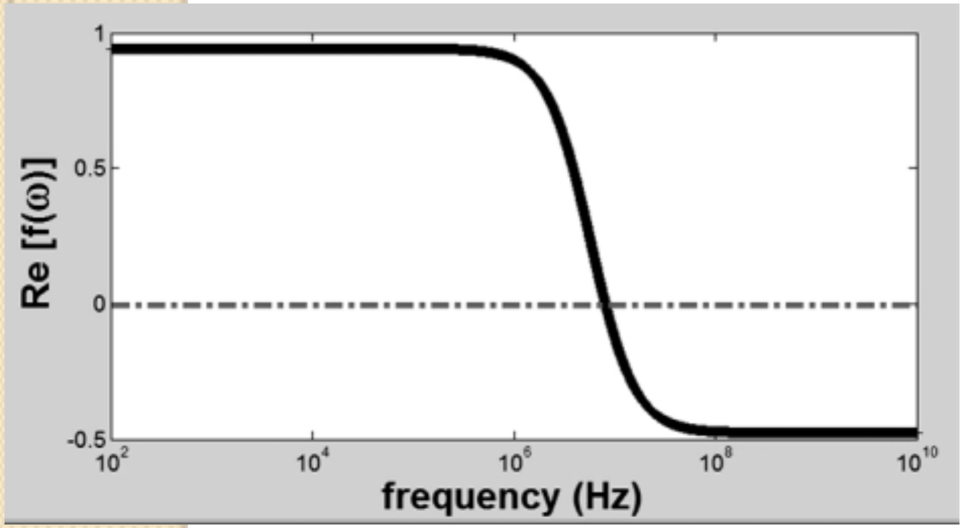


3-D vertical electrodes



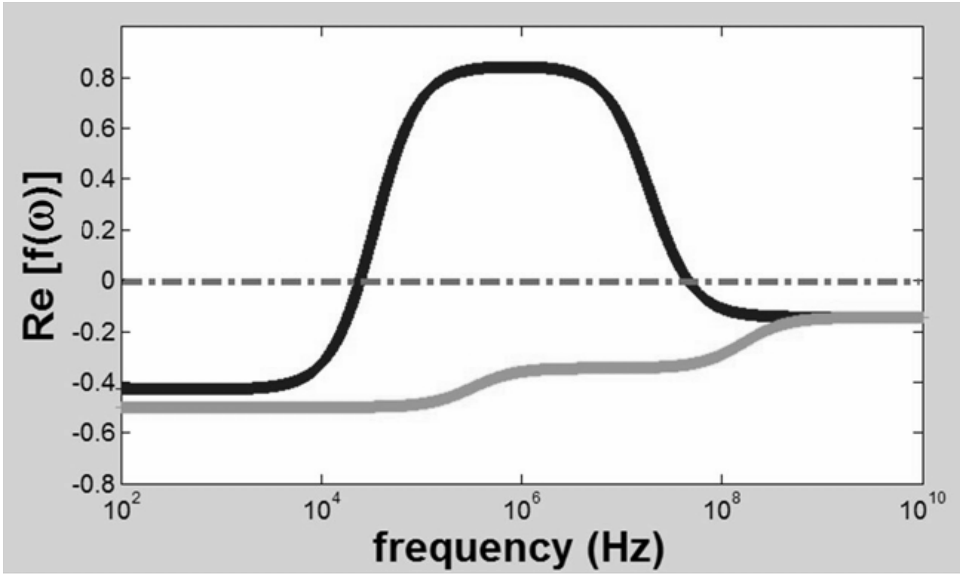
RZ Lin, CT Ho, CH Liu and HY Chang, Biotechnol. J. 2006, 1, 949–957

DEP spectrum



The normalized DEP spectrum of Re[*fcm*(*ω*)] as a function of frequency for a homogenous particle.

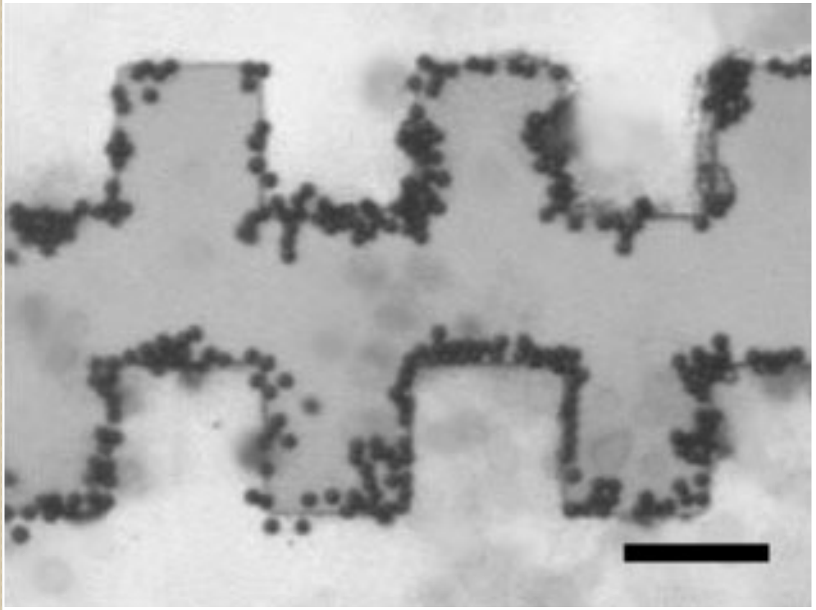
The frequency-dependent DEP spectrum for a mammalian cell using a single-shell model.



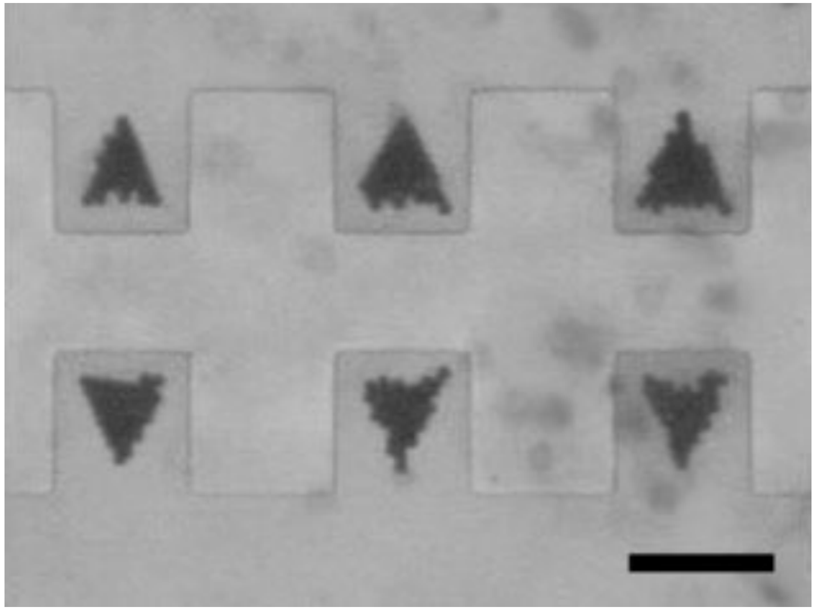
RZ Lin, CT Ho, CH Liu and HY Chang, DEP based-cell patterning for tissue engineering, Biotechnol. J. 2006, 1, 949–957

Typical DEP response for particles

Positive DEP of 7-μm polystyrene beads

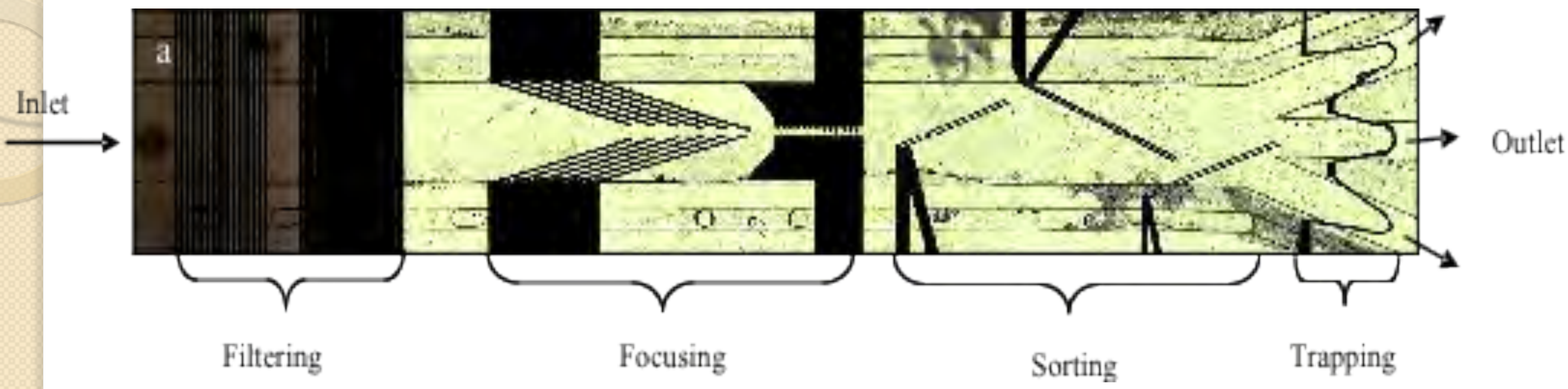


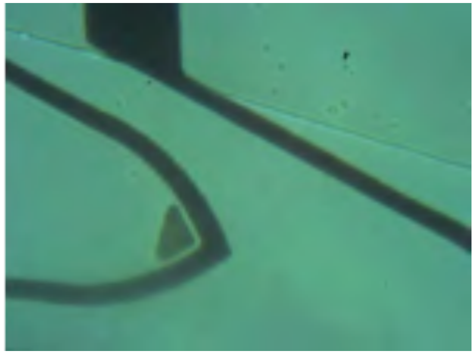
Negative DEP of polystyrene beads

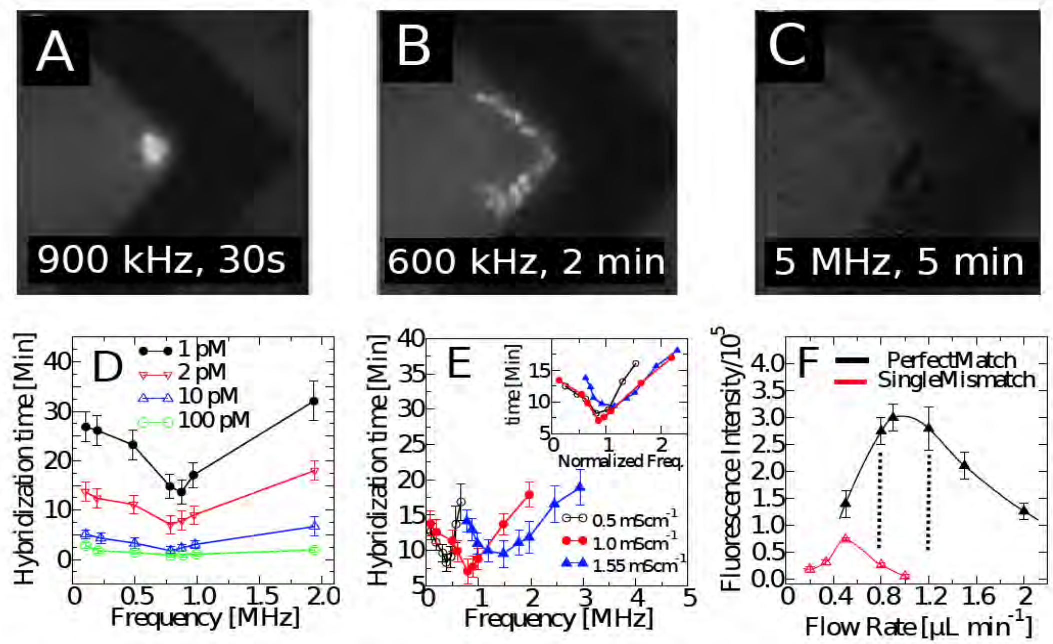


RZ Lin, CT Ho, CH Liu and HY Chang, DEP based-cell patterning for tissue engineering, Biotechnol. J. 2006, 1, 949–957

Shear & DEP enhanced CNT sensor



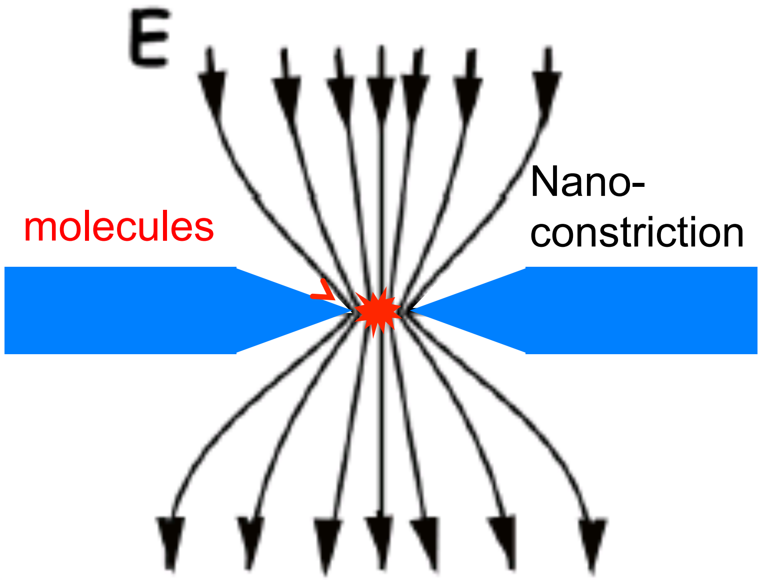




Basuray, S., S. Senapati, *et al.* (2009). "Shear and AC Field Enhanced Carbon Nanotube Impedance Assay for Rapid, Sensitive and Mismatch-Discriminating DNA Hybridization." *ACS Nano* 3: 1823.

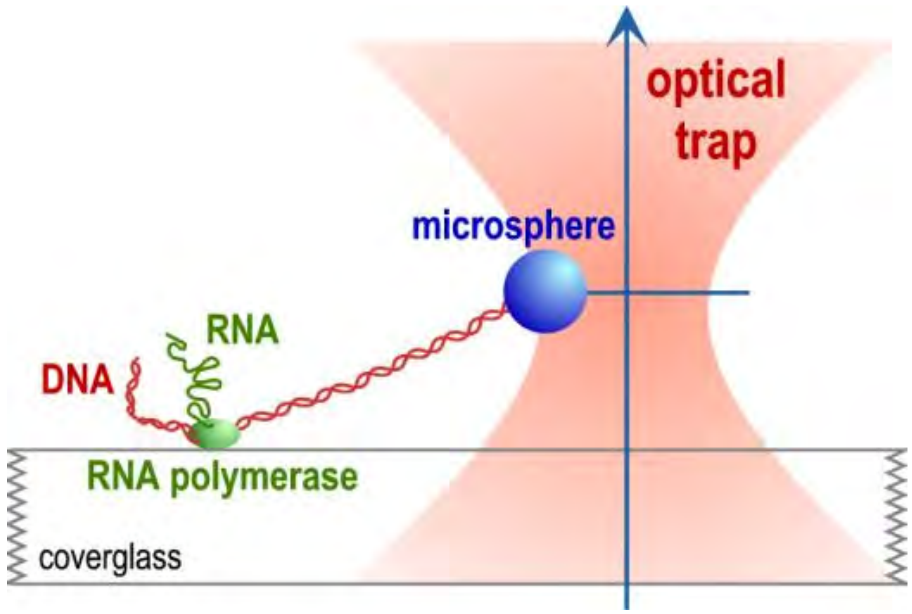
EDEP Molecular Trap vs. Optical Trap

EDEP molecular trap



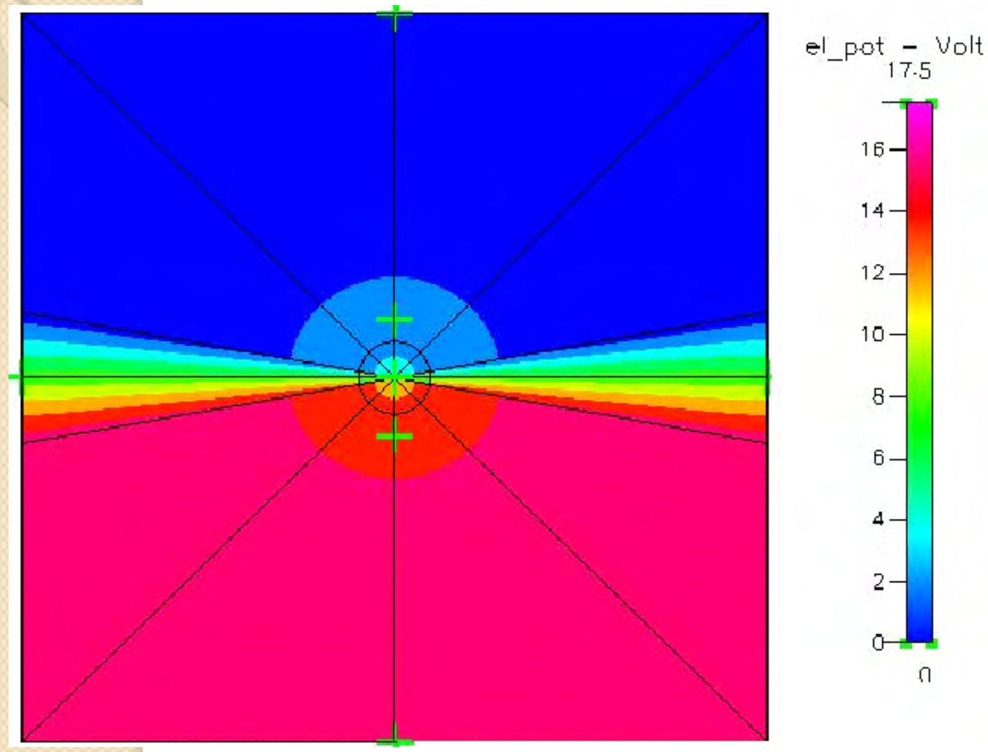
Electric field focused at the constriction

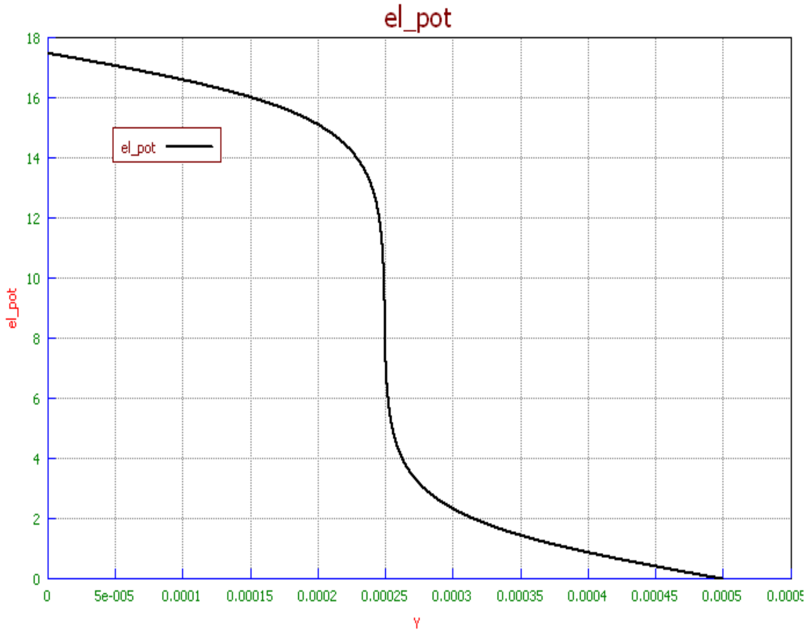
Optical trap



Electric field focused at the focal point

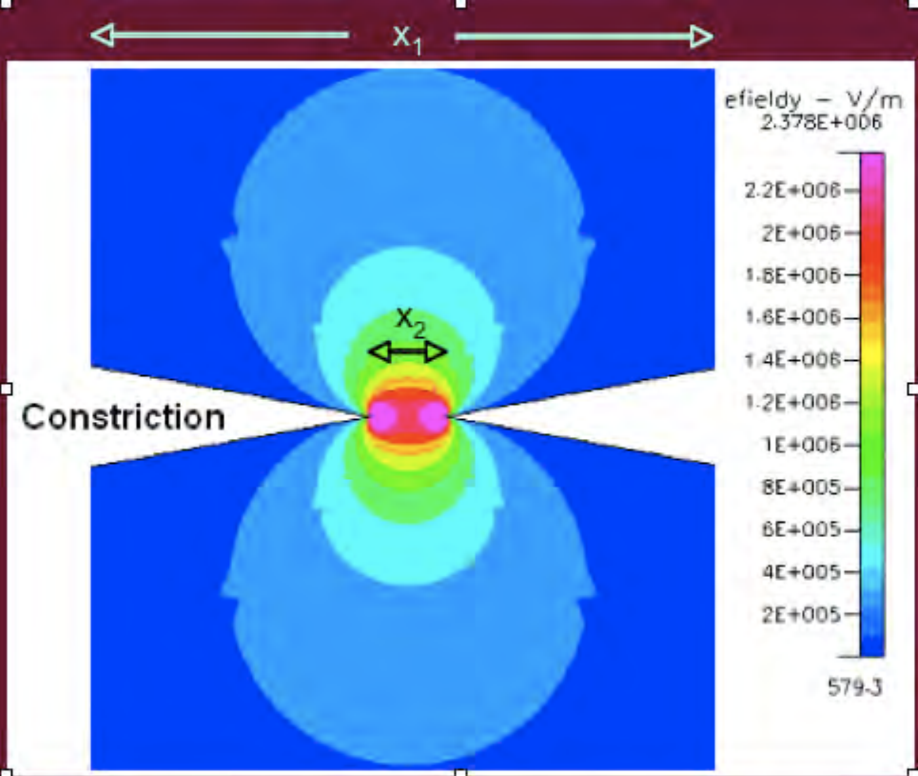
Electric Potential Distribution

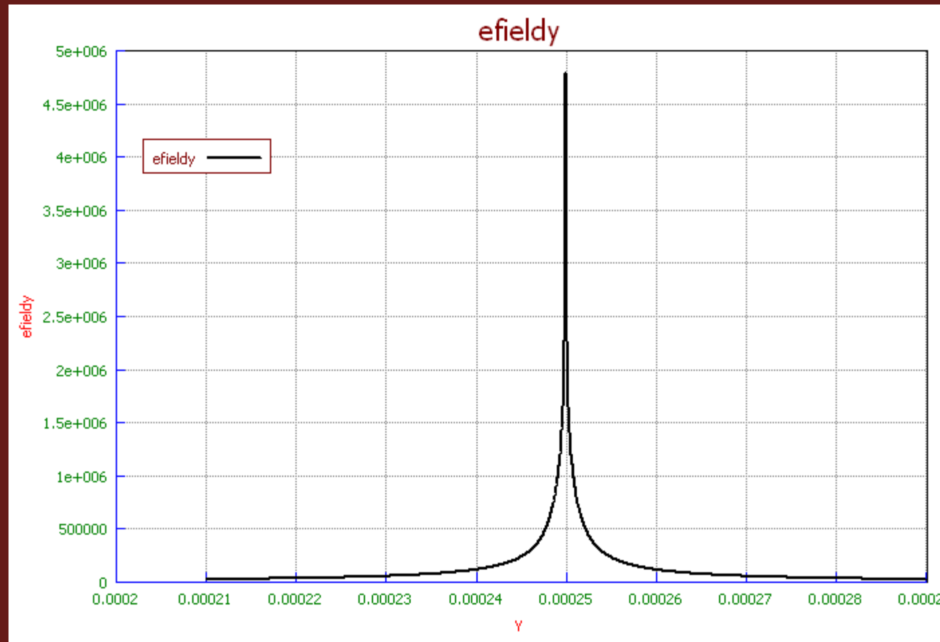




Potential drop mostly occurs at the constriction

Electric Field Enhancement





Field focusing factor: (x_1/x_2) (z_1/z_2)

For 50 μm/50 nm:

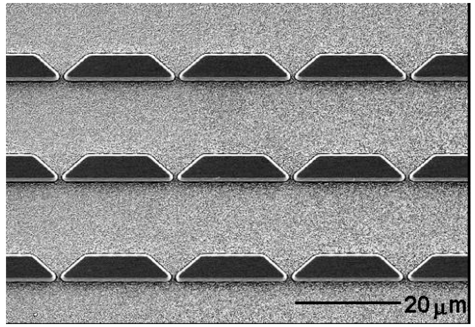
$E \rightarrow 10^3$ x

$\nabla(E^2) \rightarrow 10^6$ x

Field focusing mostly occurs at the (tips of) constriction

Electrodeless DEP for DNA concentration
–Field response at a fixed frequency

368bp, 1000 Hz in 0.5xTBE



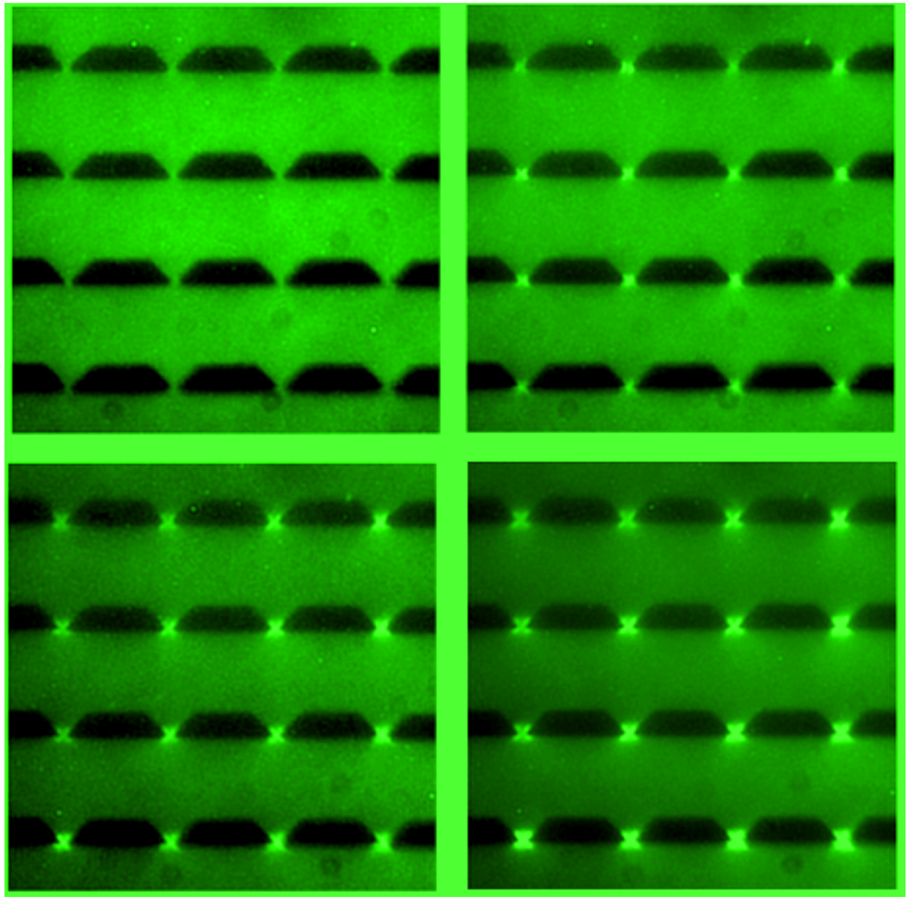
▲ E ▼

200 Vpp/cm

1 Vpp/unit cell

400 Vpp/cm

2 Vpp/unit cell



800 Vpp/cm

4 Vpp/unit cell

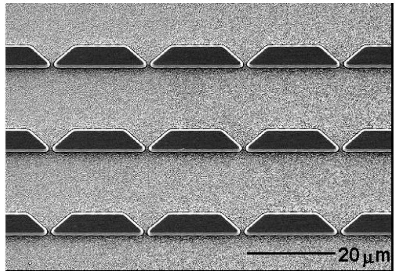
1000 Vpp/cm

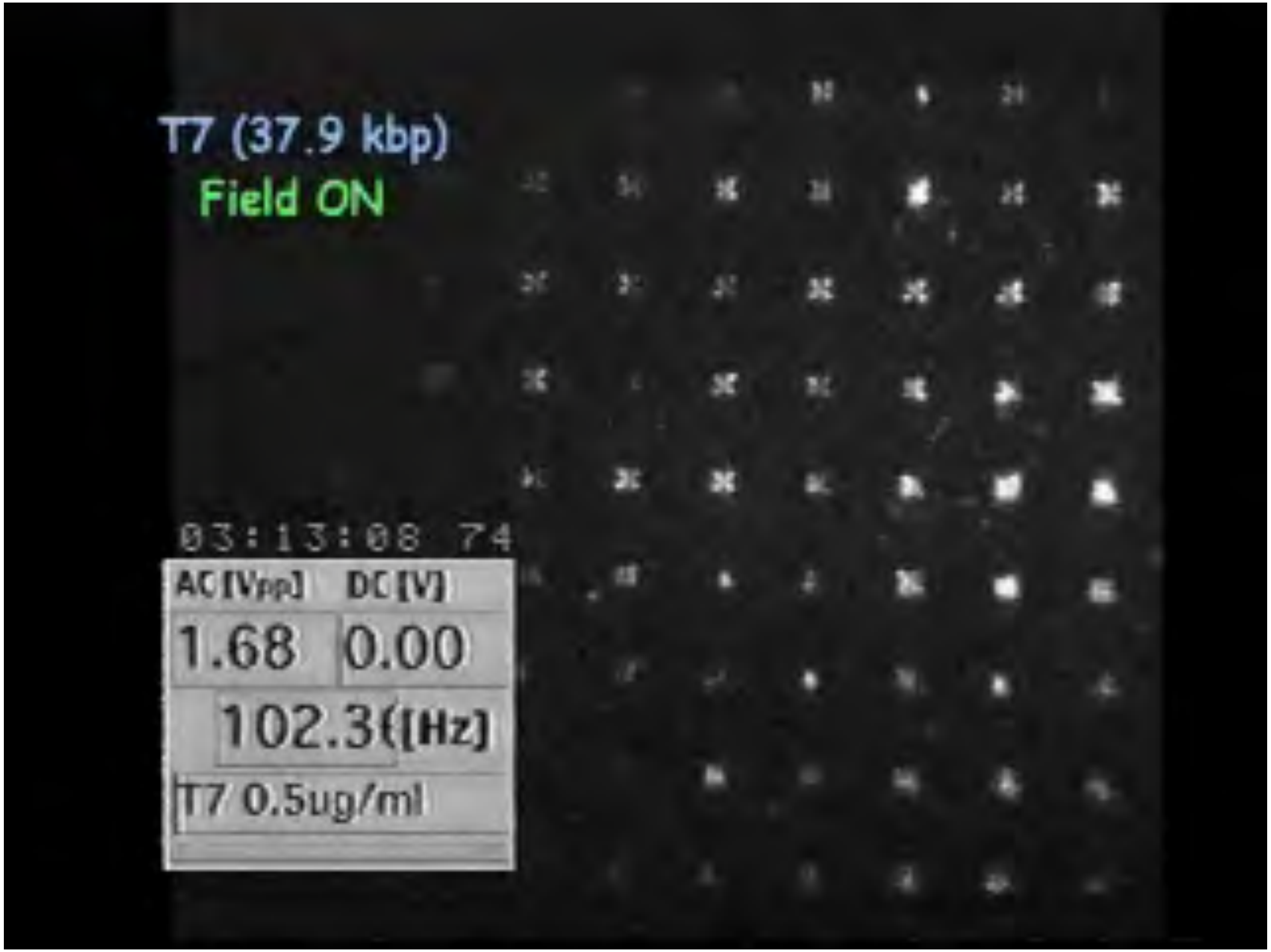
5 Vpp/unit cell

Chou et al., Biophys. J. 83: 2170-2179 (2002)

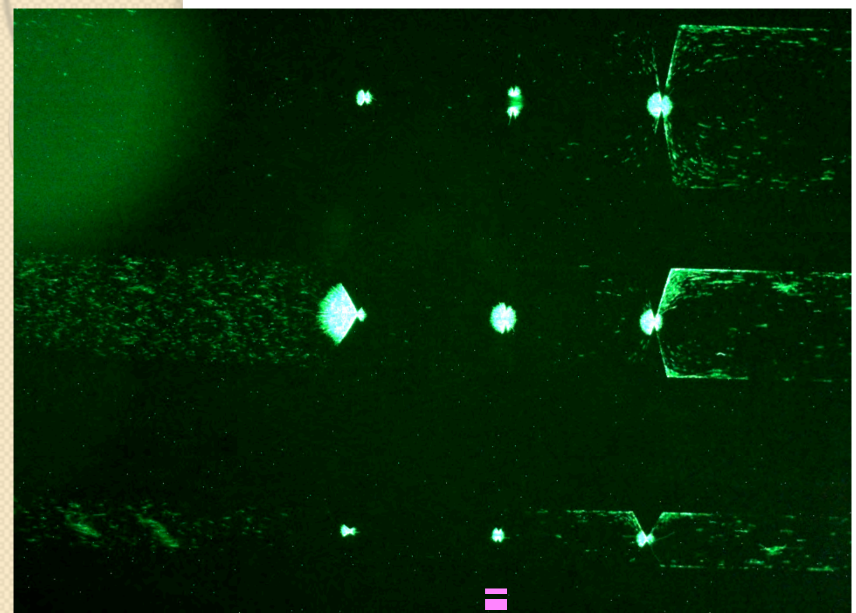
US Patent # 6,824,664 (2004)

EDEP–Trapping of DNA (movie)



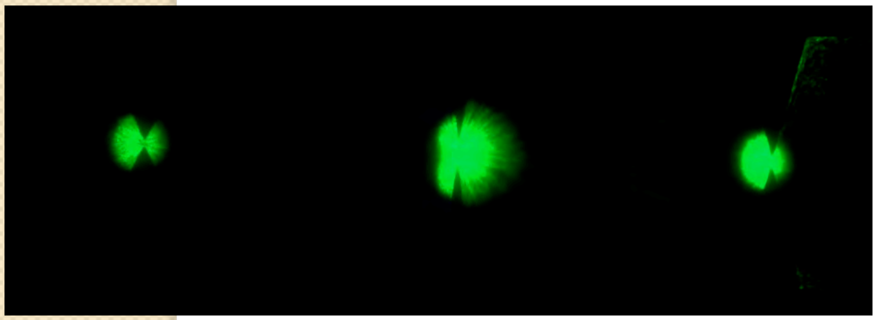


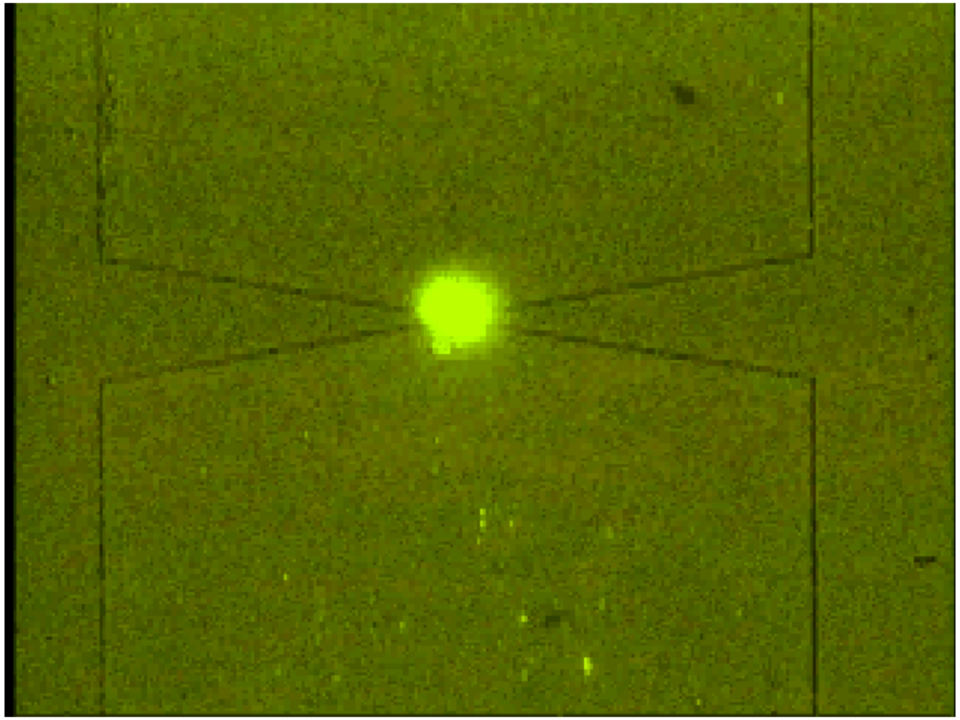
EDEP Array for Cell *E. coli* Trapping



4 μm constriction,
10 μm deep
50-2 MHz, 100 Vpp/cm
Buffer salt concentration:
up to 100 mM

Enrichment ~ 10^{3-4}



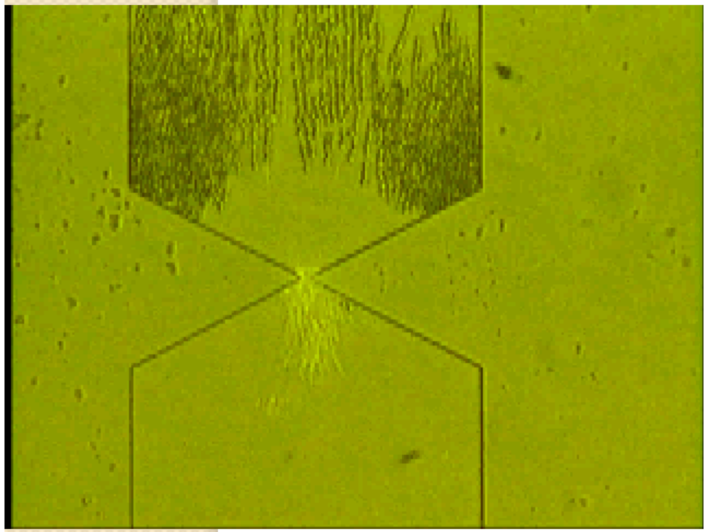


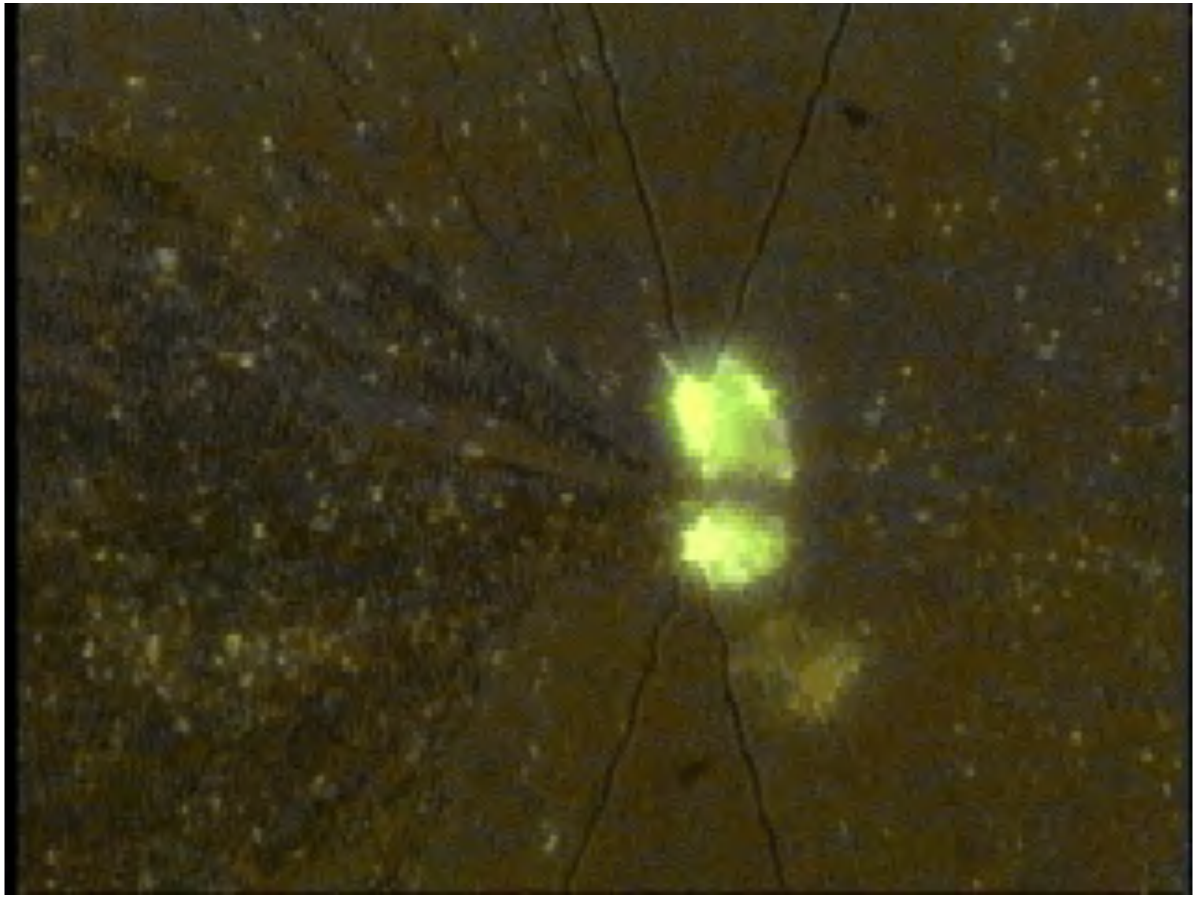
C. F. Chou, F. Zenhausern (2003) IEEE Eng. Med. Biol. Mag. Nov/Dec. 62-67.

EDEP Array for Cell Separation

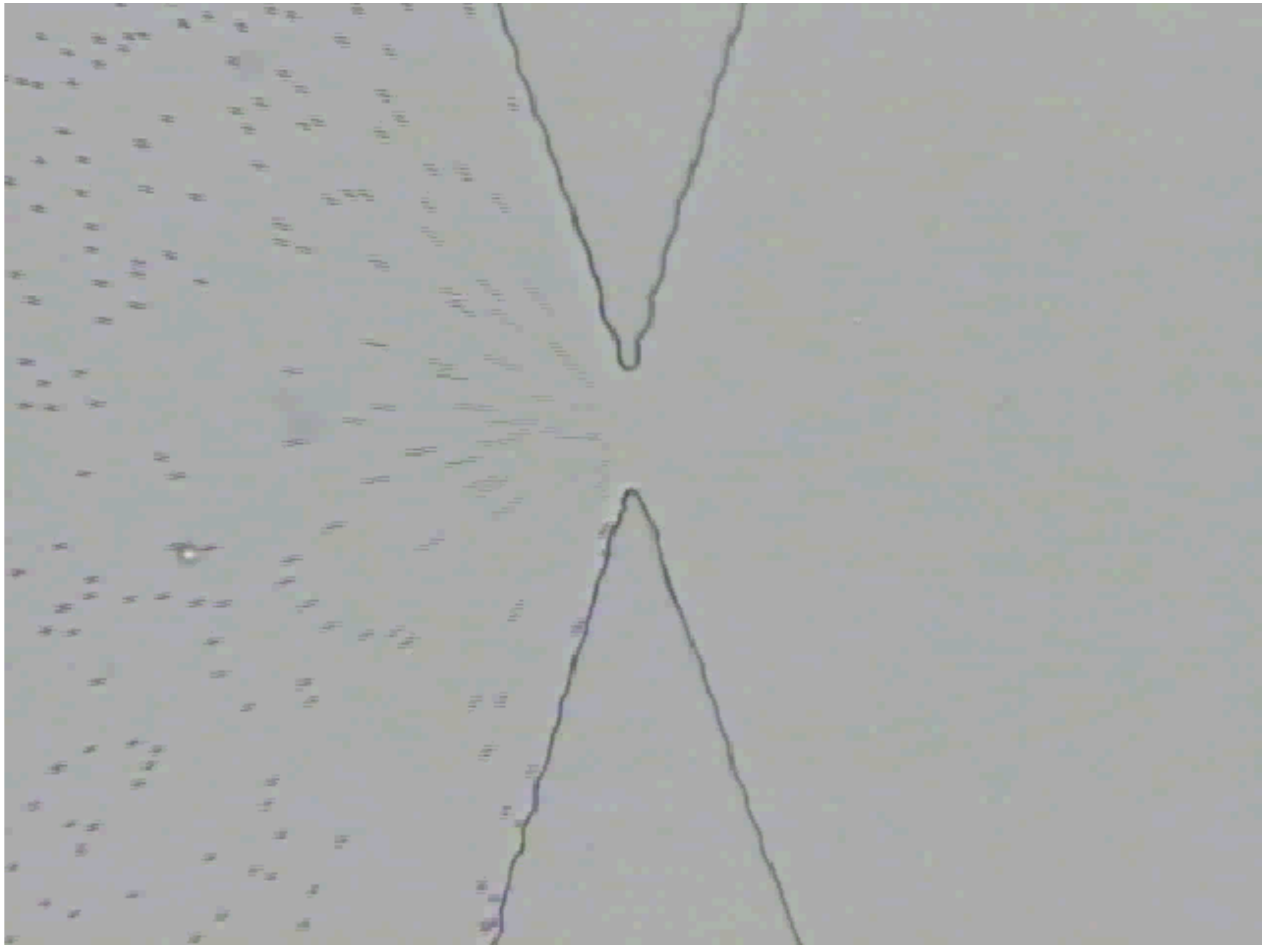
Device: PDMS/glass

RBC (– DEP) and *E. coli* (+ DEP)



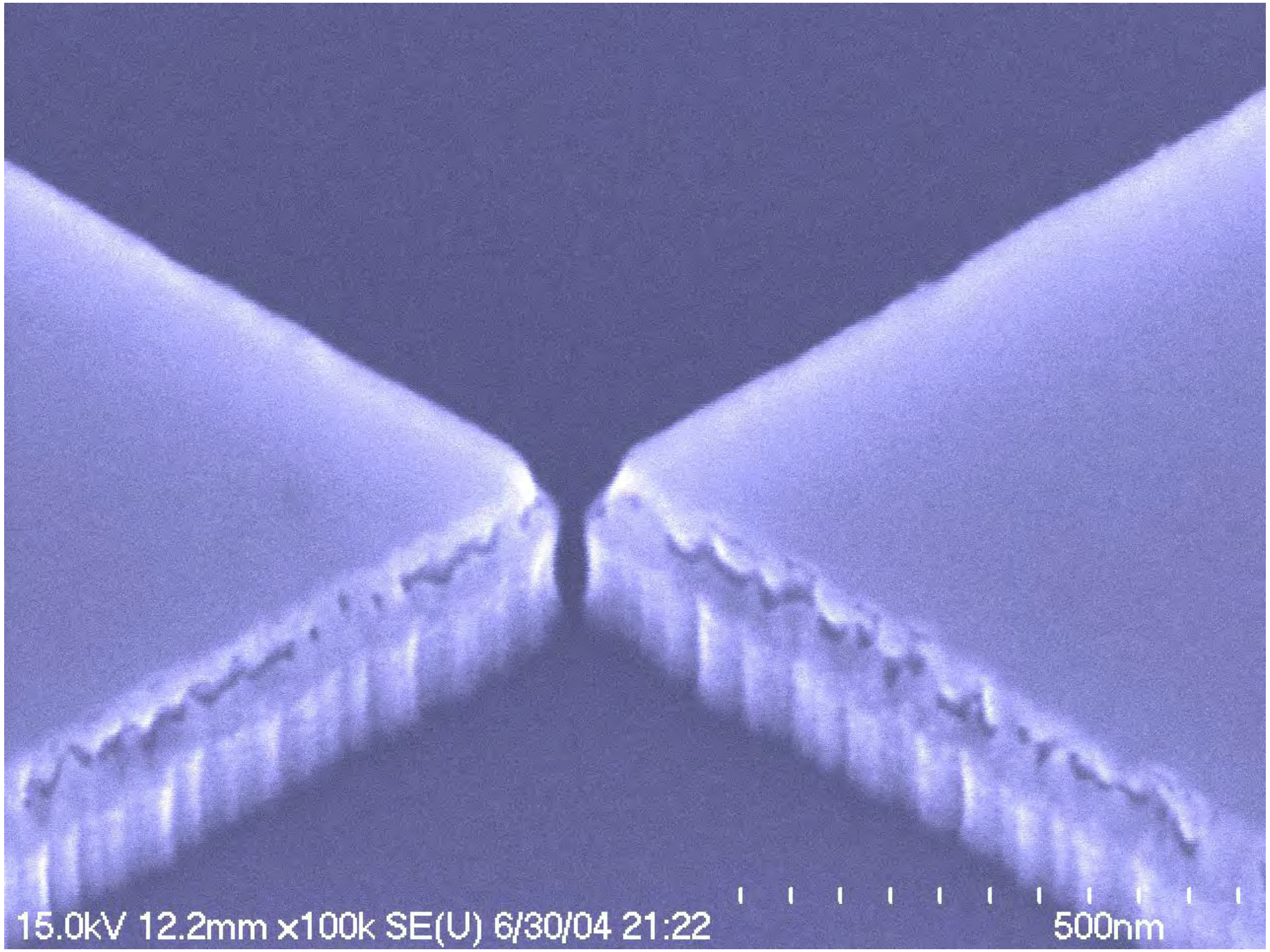


High field for cell lysing



C. F. Chou, F. Zenhausern (2003) IEEE Eng. Med. Biol. Mag. Nov/Dec. 62-67.

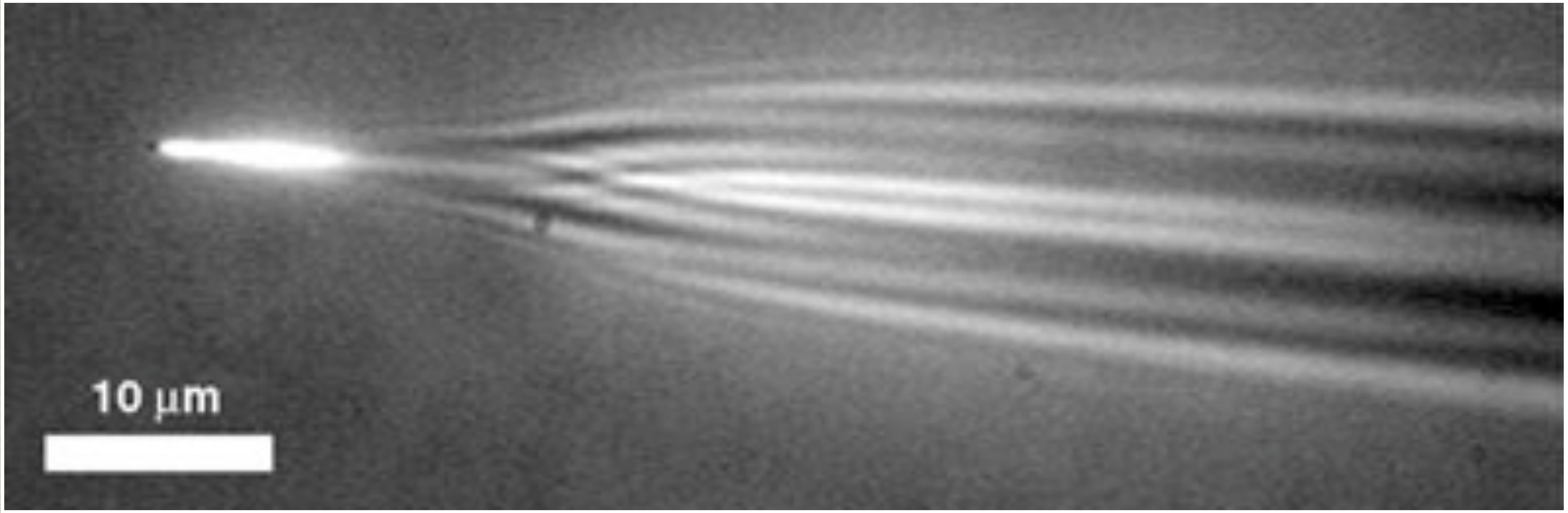
Nanoscale protein trap



50 nm gap/250 nm deep

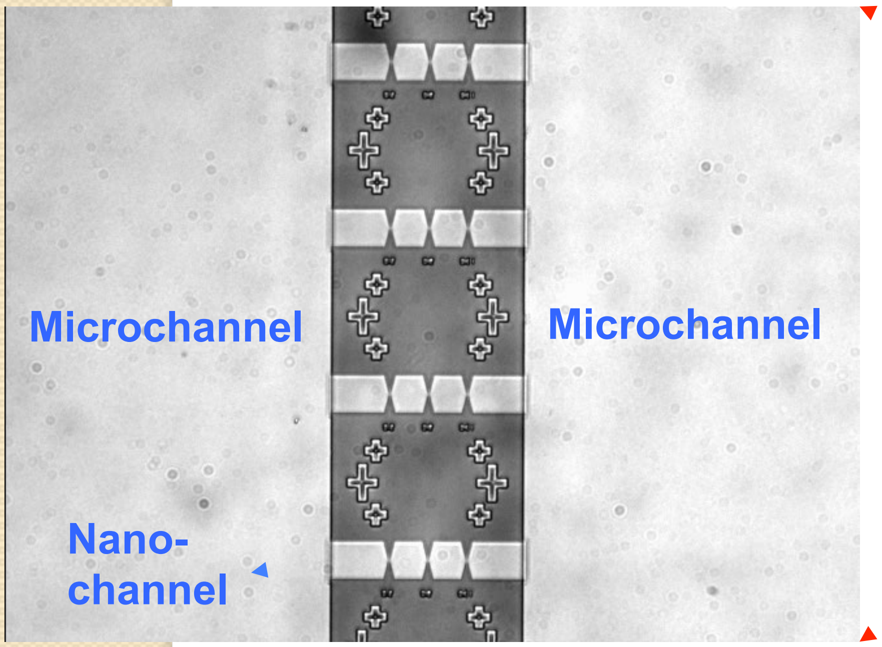
Protein trapping using nanopipette

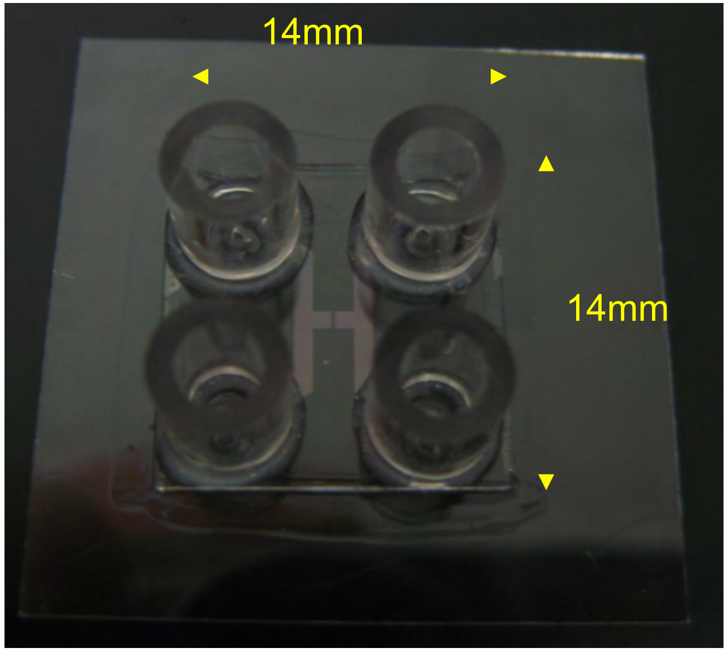
10^3-fold enhancement in seconds

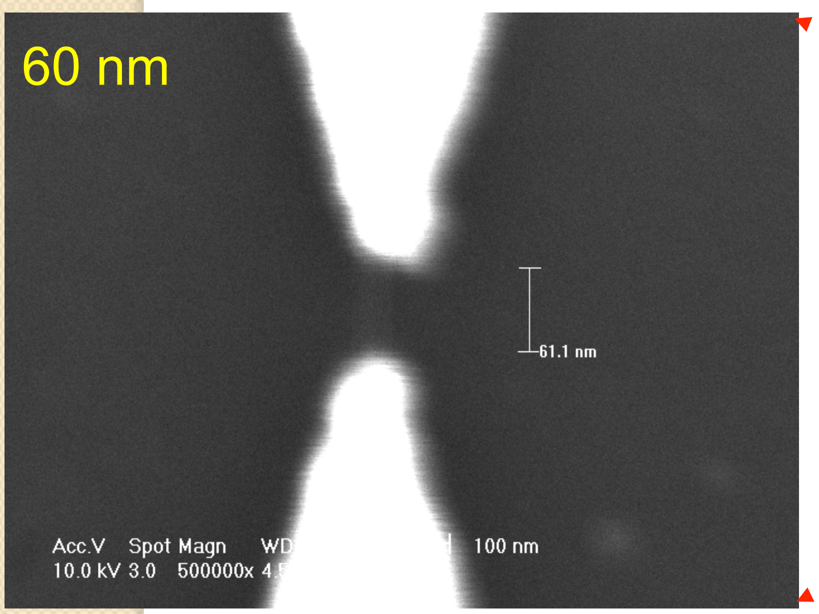


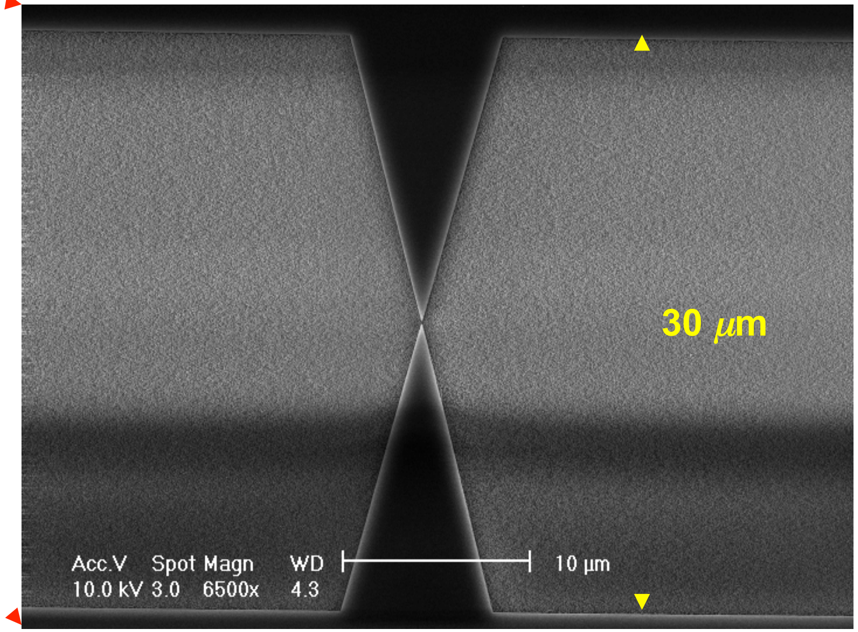
RW Clarke et al., Angew. Chem. Int. Ed. 44, 3747 (2005)

Nanoscale protein trap

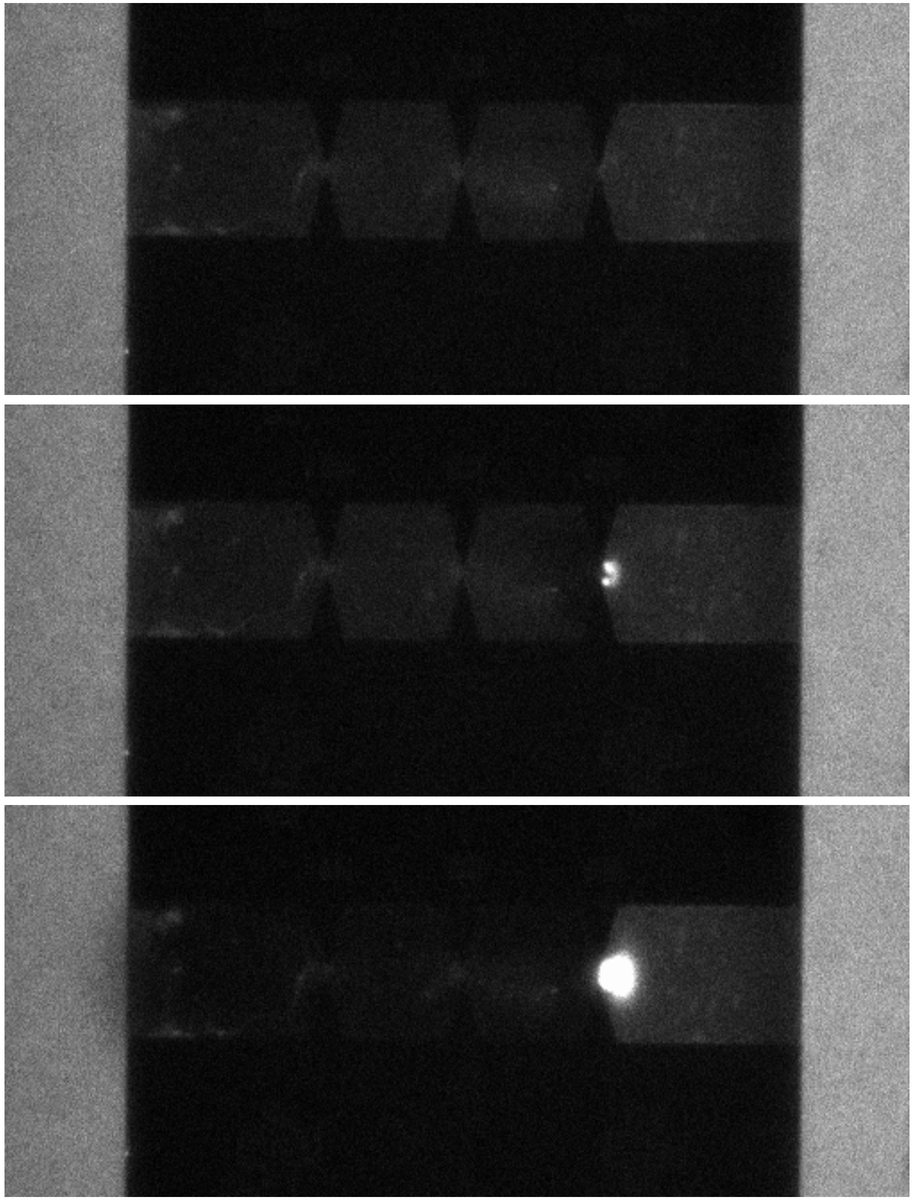








Negative DEP for protein enhancement



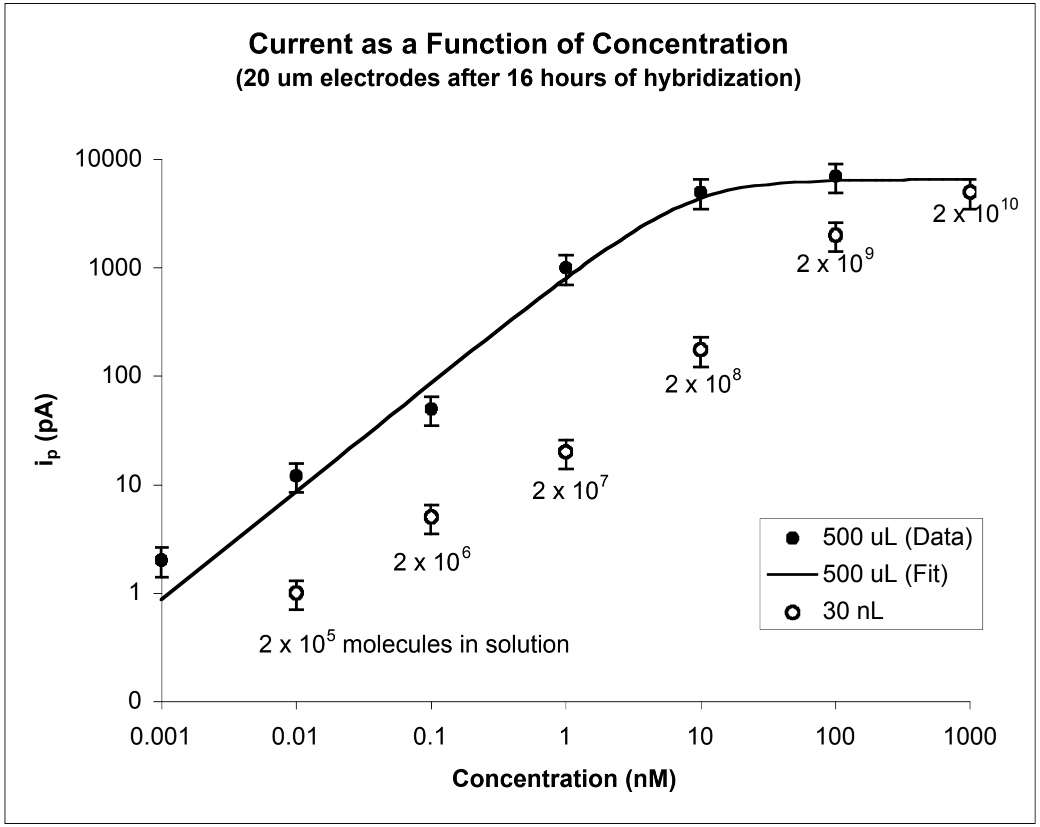
t = 0 sec

t = 0.1 sec

t = 0.8 sec

Why molecular traps?

Titration of detection limit with microelectrodes in microchamber



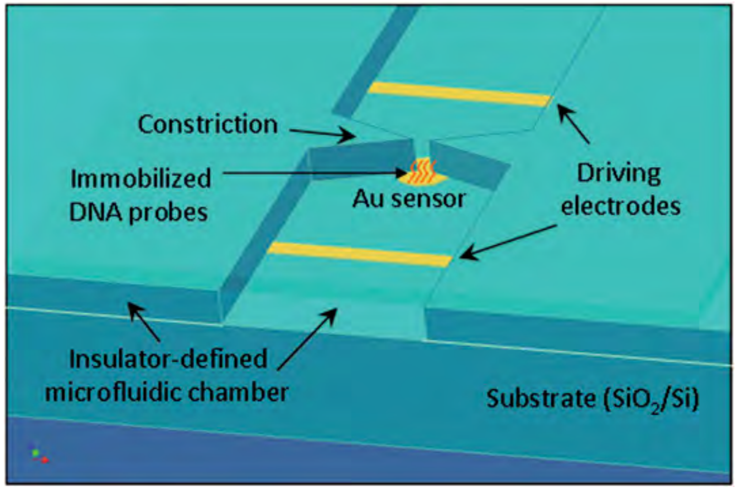
N. Swami

This data set demonstrates a chief bottleneck for *all* miniaturized sensing methods in general, and surface binding assays in particular. This is associated with the chemical kinetic limits to sensitivity upon miniaturization. → Solution: sample pre-concentration!!

DEP applications on DNA/protein sensors

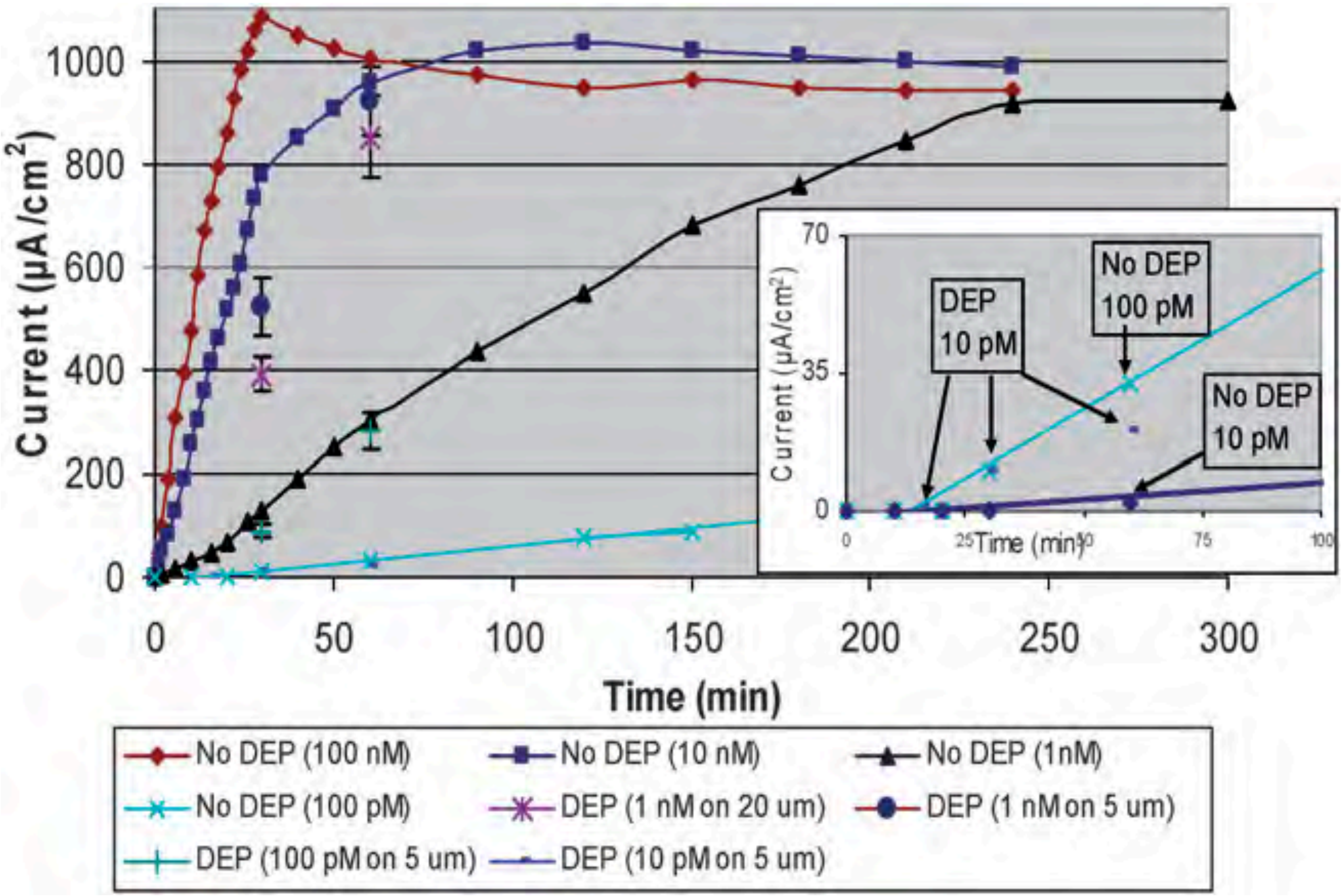
Hybridization kinetics enhancement by sample preconcentration

Second order kinetics: $Ct_{1/2} = 1/k$
C = probe concentration (moles/liter)
k = Rate constant
$t_{1/2}$= the time in seconds it takes for a probe of given concentration to reach 50% annealed.



Concentration enhancement	Annealing time of hybridization 50%	75%	95%
1x	10 hrs	30 hrs	100 hrs
100x	6 min	18 min	60 min
1000x	36 sec	1.8 min	6 min

Enhanced DNA sensor kinetics

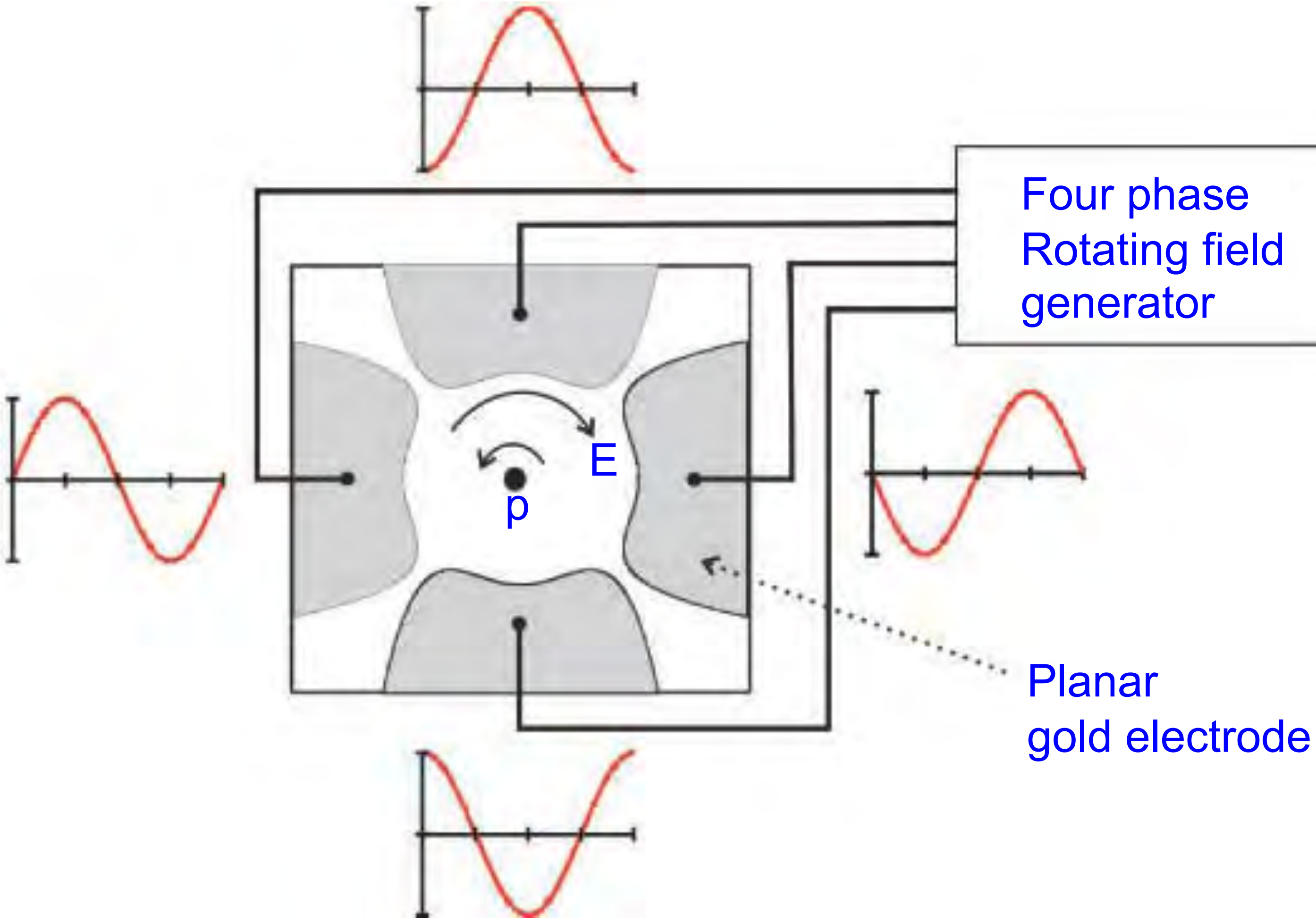


Swami, N., C.F. Chou, *et al.* (2009). "Enhancing DNA Hybridization Kinetics through Constriction-Based Dielectrophoresis." Lab on a Chip 9: 3212-3220.

Phenomena associated with DEP:

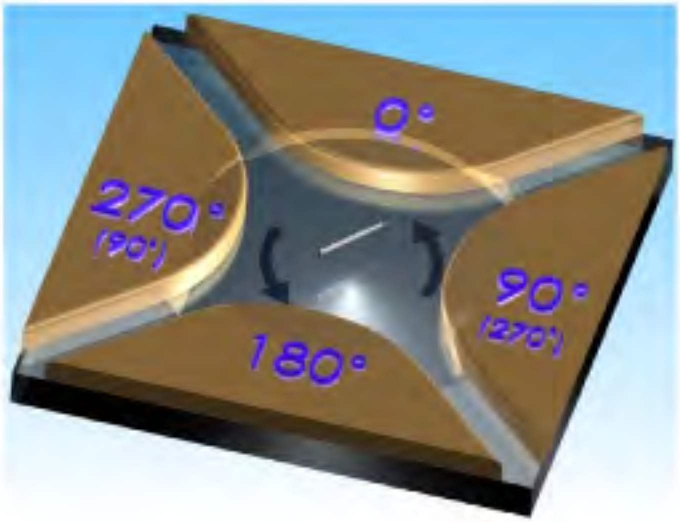
- Electrorotation and traveling wave DEP (TWDEP)
- Field-flow fractionation DEP (FFF-DEP)
- Optoelectronic tweezers

Electrorotation and traveling wave DEP

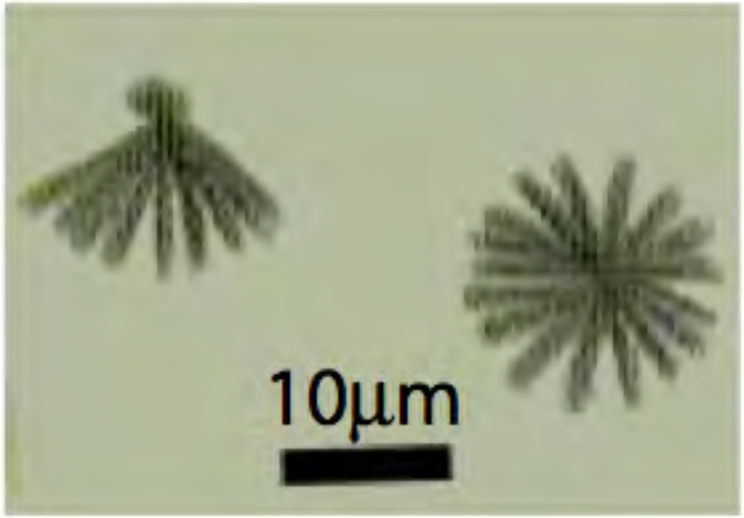


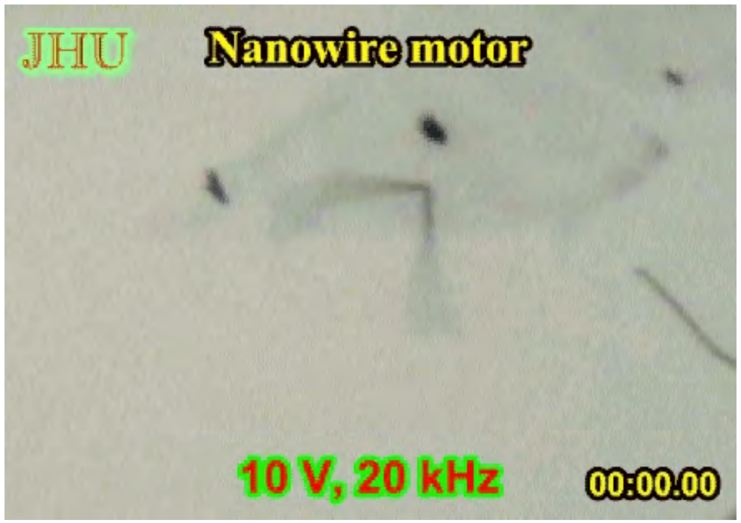
Controllable High-Speed Rotation of Nanowires

(a)



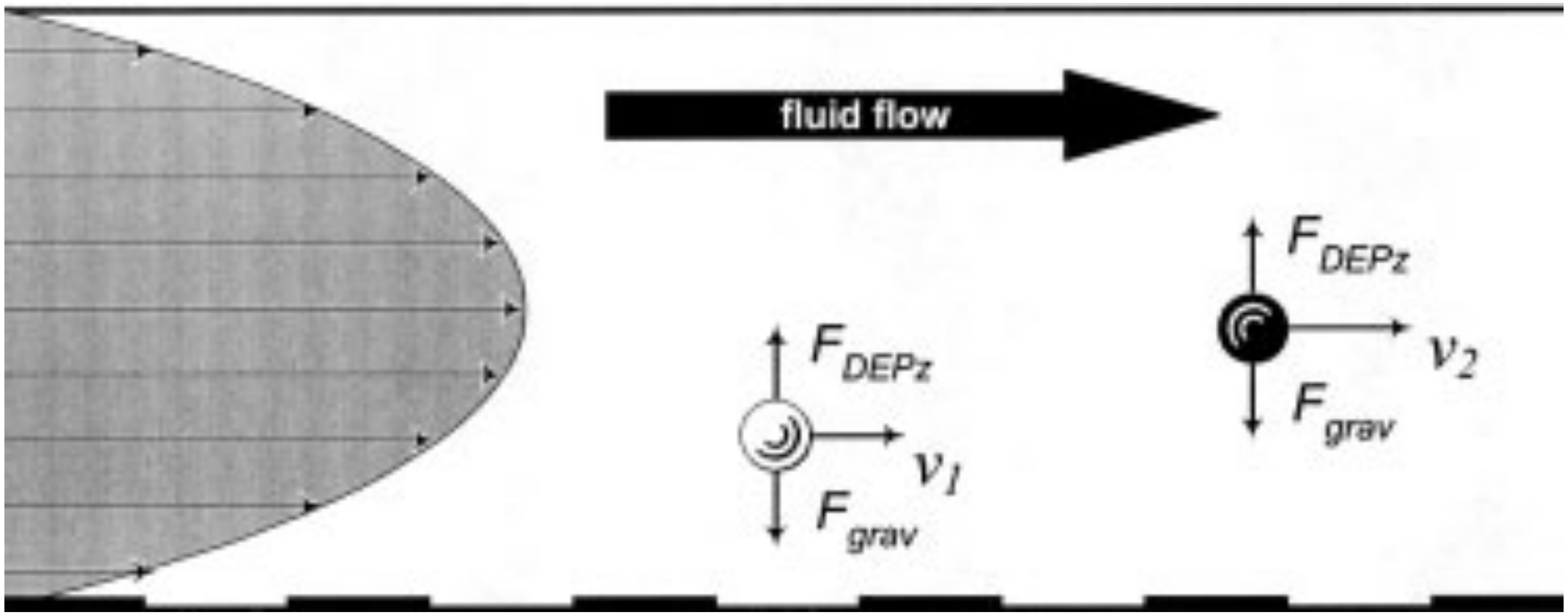
(b)





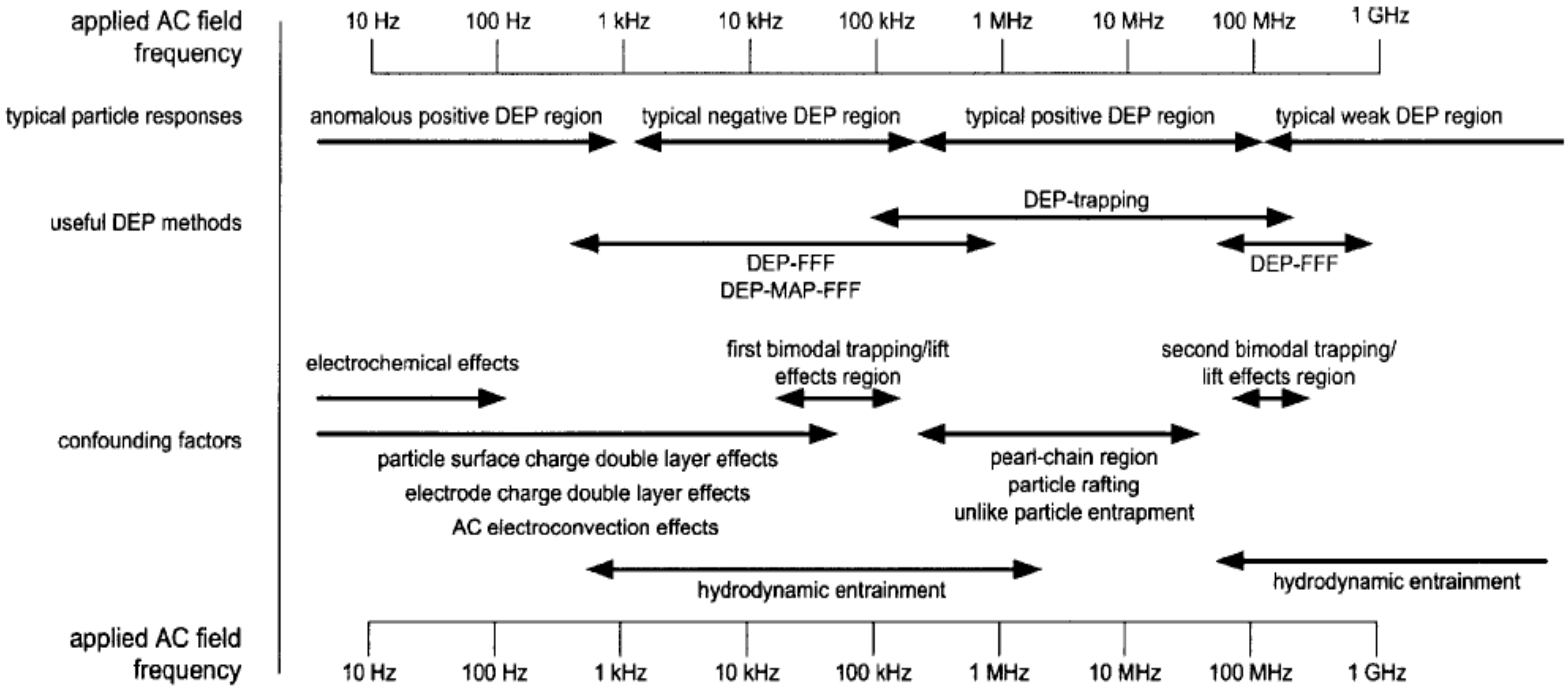
D. L. Fan, F. Q. Zhu, R. C. Cammarata, C. L. Chien, *PRL* 94, 247208 (2005)

Principle of hyperlayer DEP-FFF



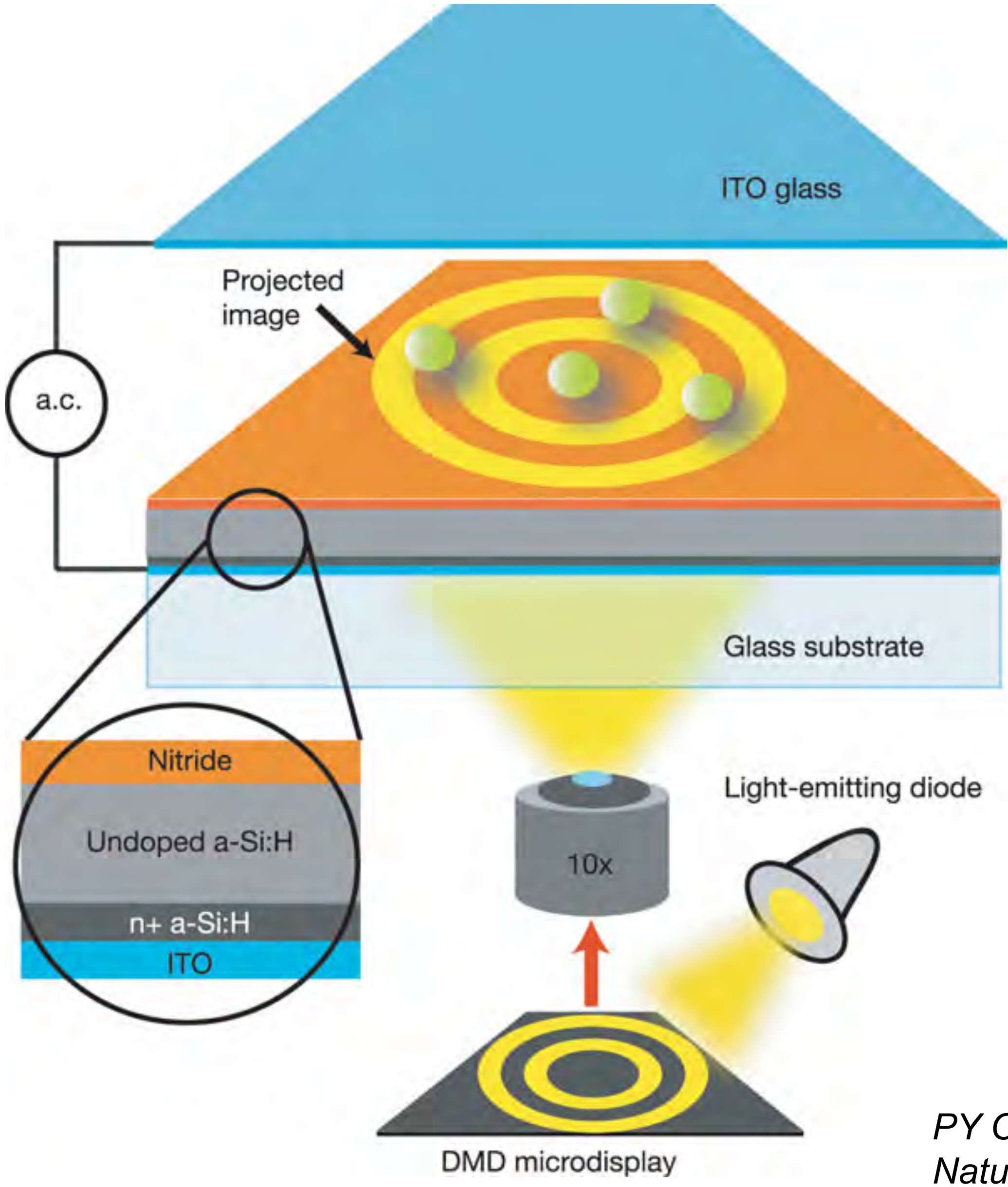
PRC Gascoyne & J Vykoukal, "Particle separation by dielectrophoresis"
Electrophoresis 2002, 23, 1973–1983.

Guide to frequency bands for various DEP phenomena



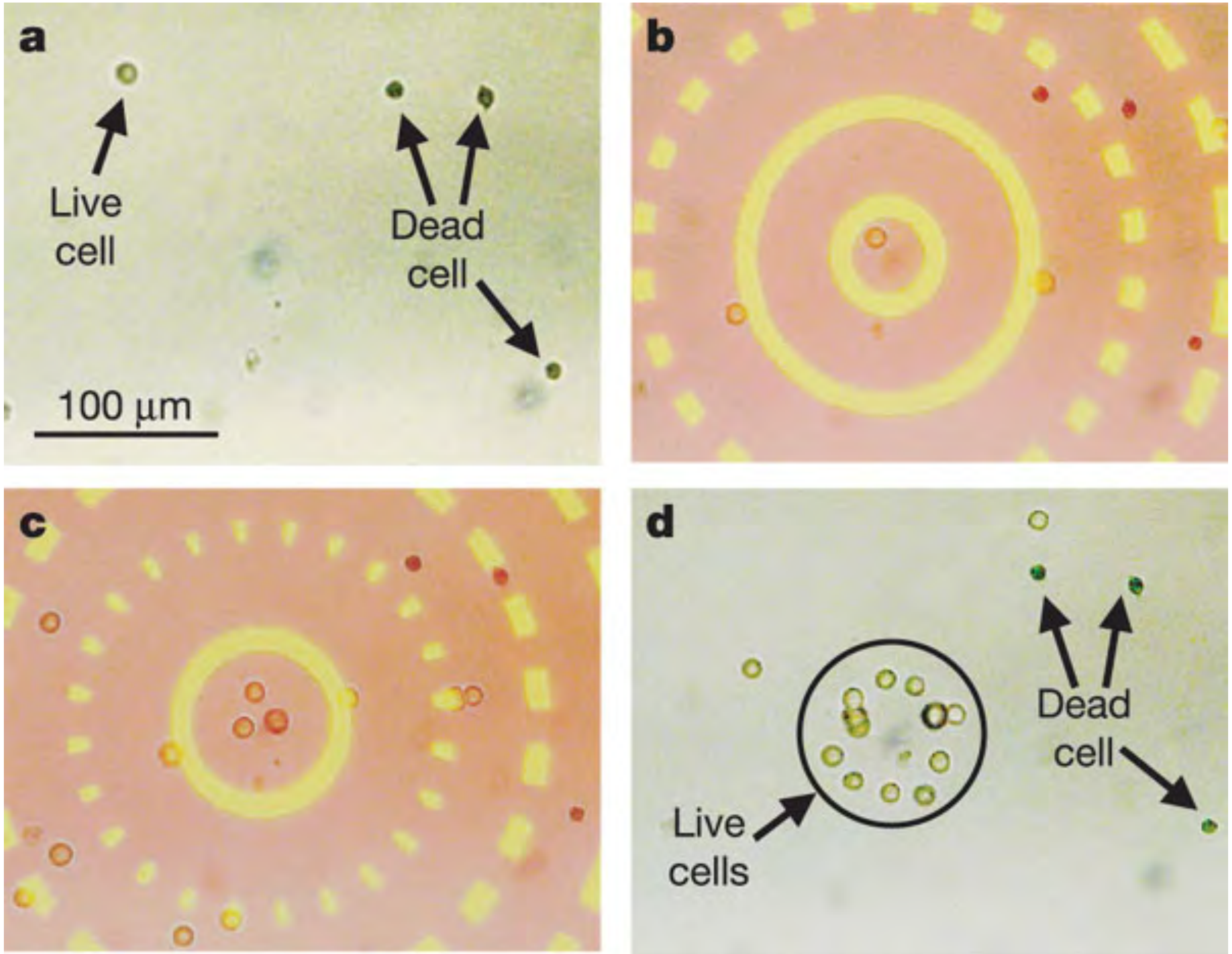
PRC Gascoyne & J Vykoukal, "Particle separation by dielectrophoresis"
Electrophoresis 2002, 23, 1973–1983.

Optoelectronic tweezers



PY Chiou, AT Ohta, MC Wu, Nature 436, 370-372 (2005)

Optoelectronic tweezers—cell sorting



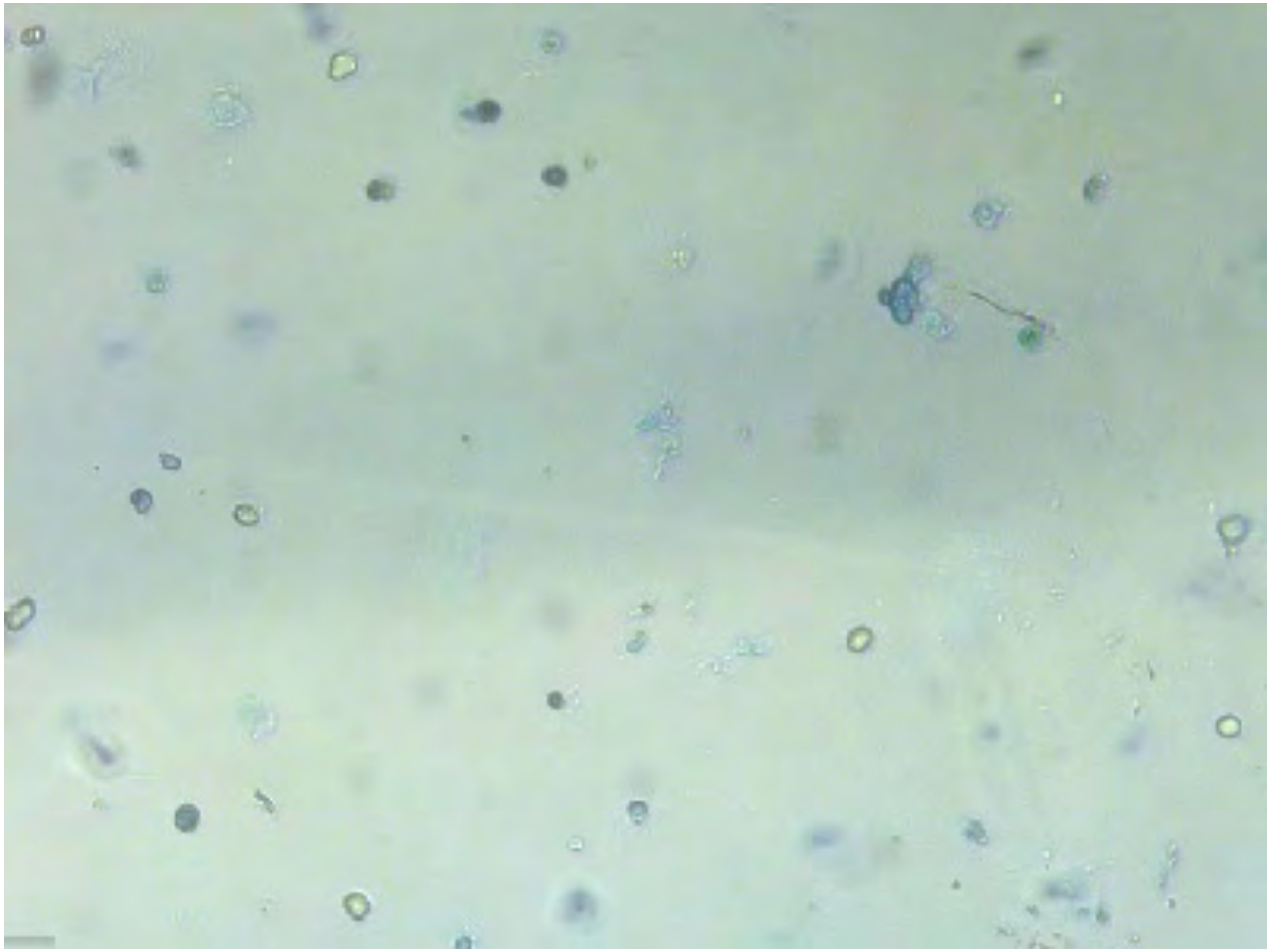
PY Chiou, AT Ohta, MC Wu, Nature 436, 370-372 (2005)

Optoelectronic tweezers

Cell sorting—live & dead cells

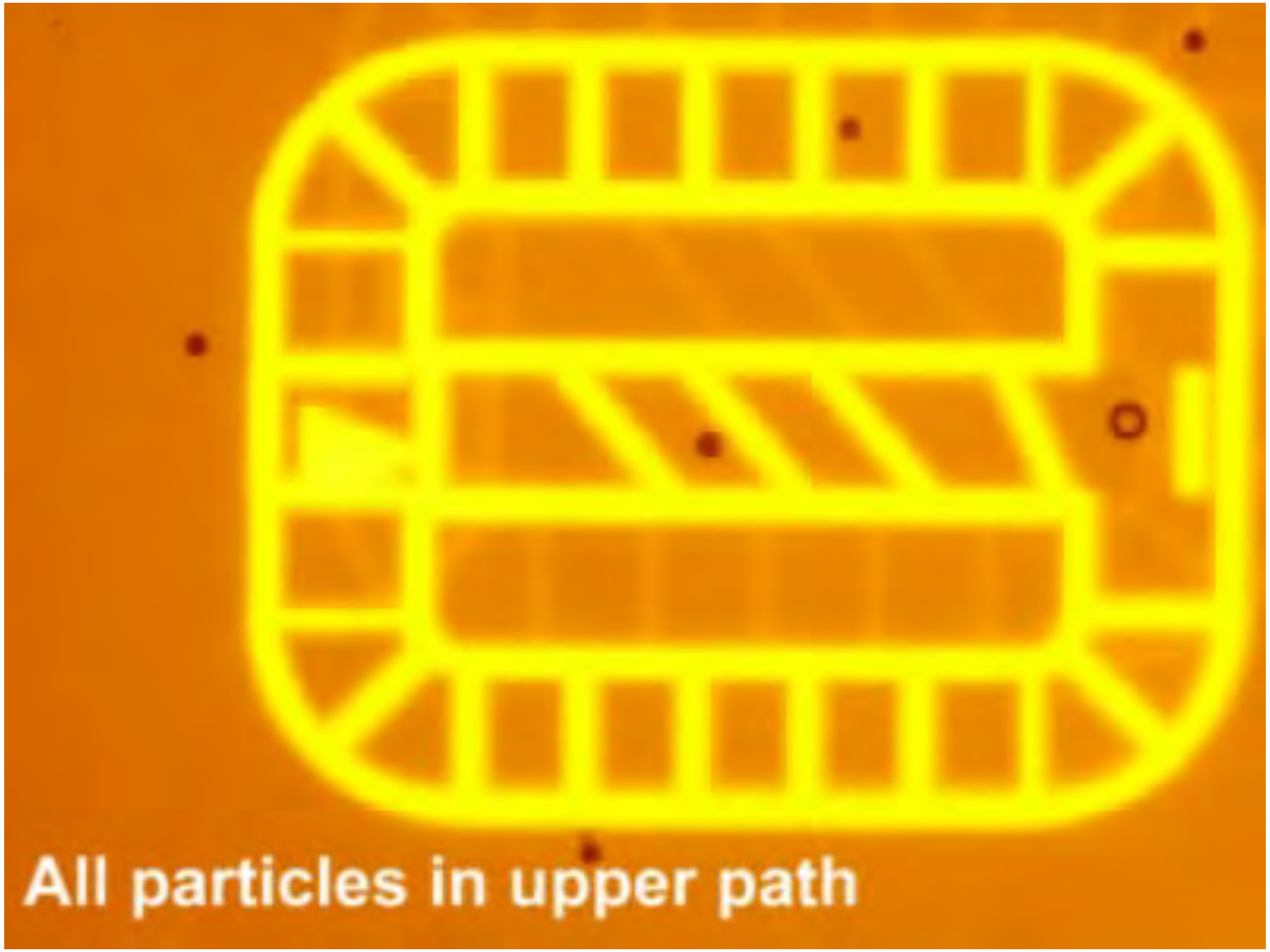
The selective concentration of live human B cells is accomplished using positive OET

(Movie)



PY Chiou, AT Ohta, MC Wu, Nature 436, 370-372 (2005)

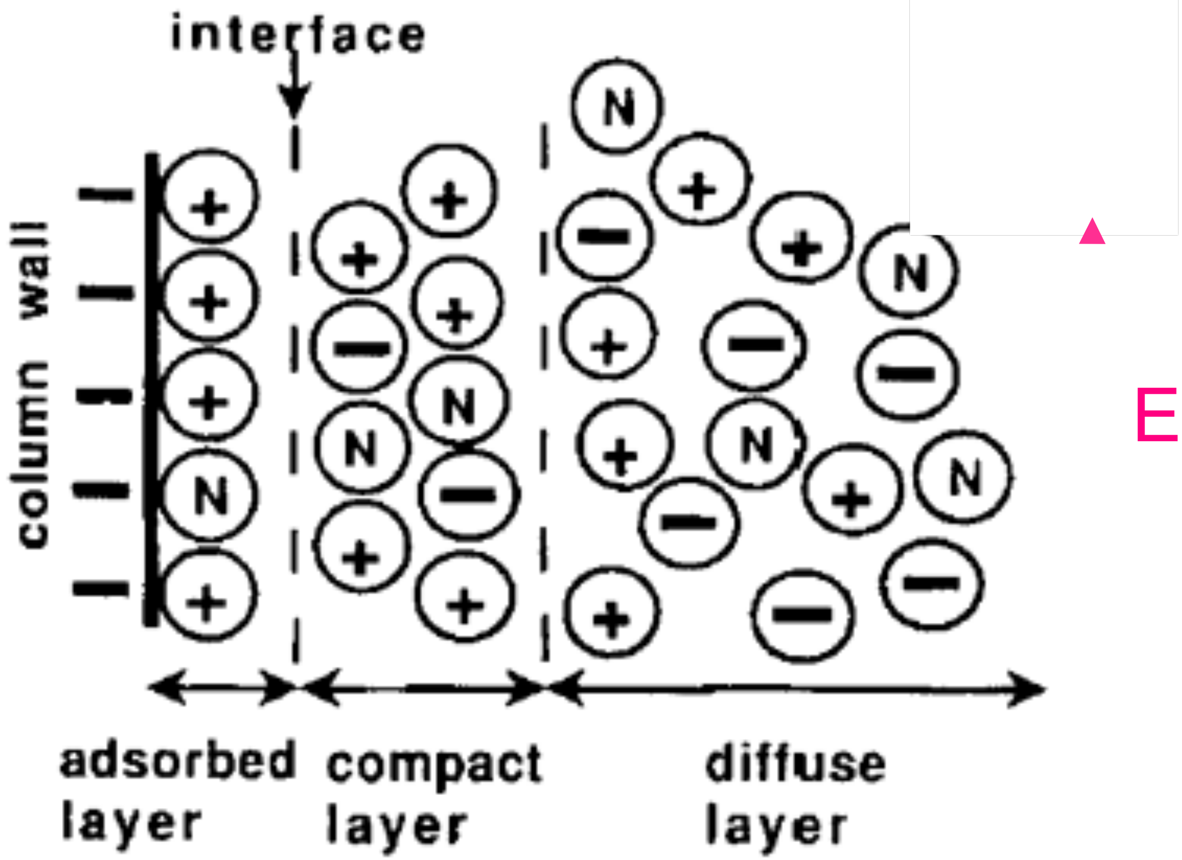
Integrated virtual optical machine



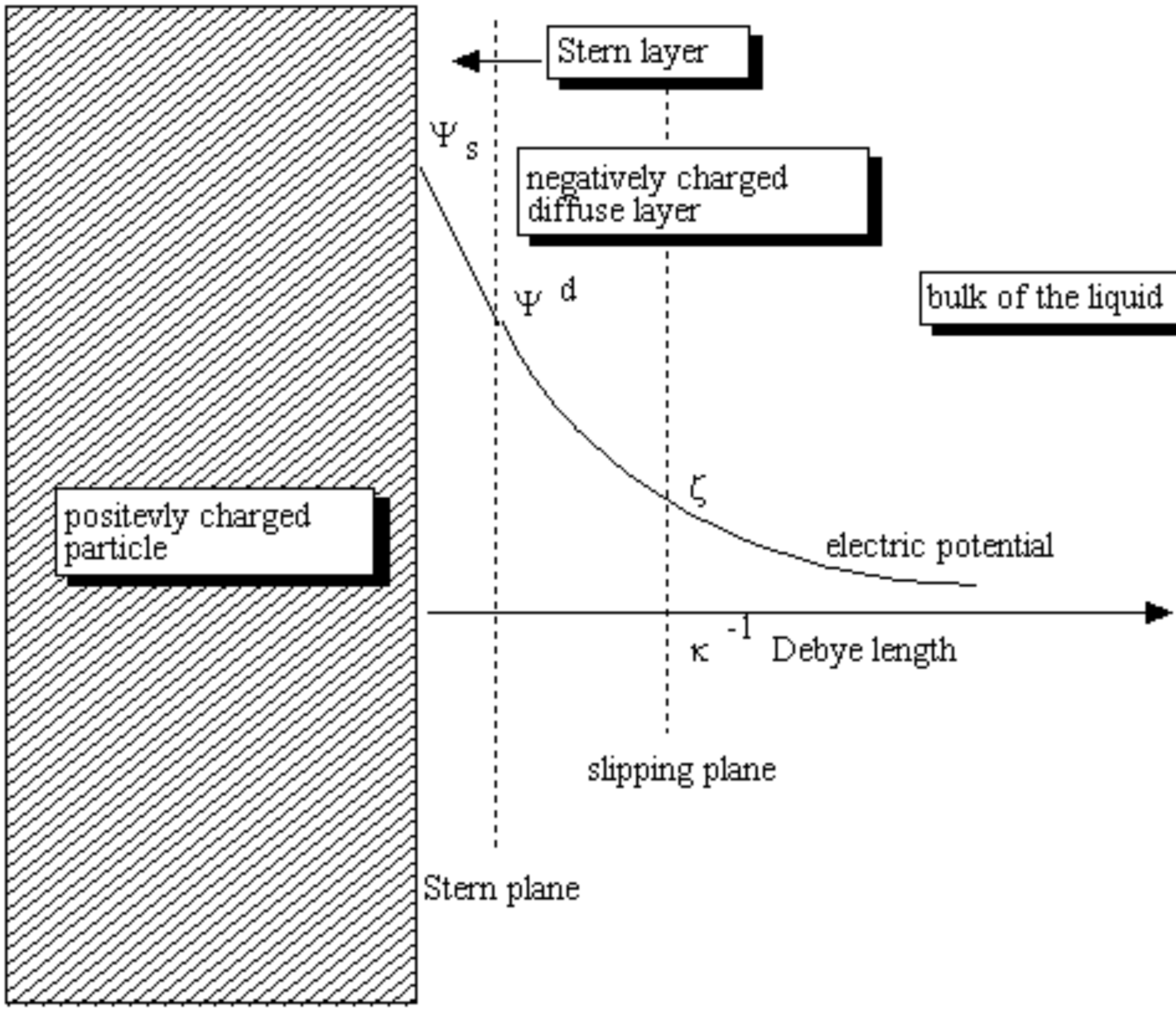
PY Chiou, AT Ohta, MC Wu, Nature 436, 370-372 (2005)

Electrical double layer

(Gouy-Chapman-Stern model)



Electrical double layer

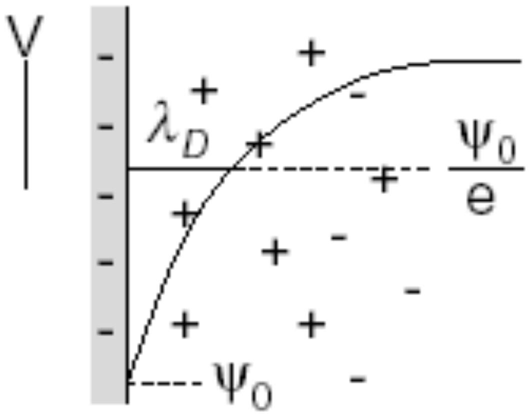


Poisson-Boltzmann Equation

Poisson Eq. $\nabla^2 \phi = -\frac{\rho_E}{\varepsilon}.$ Boltzmann distribution: $c_i = c_{i,\infty} \exp\left(-\frac{z_i F \varphi}{RT}\right).$

Poisson-Boltzmann Eq.

$$\nabla^2 \varphi = -\frac{F}{\varepsilon} \sum_i c_{i,\infty} z_i \exp\left(-\frac{z_i F \varphi}{RT}\right).$$



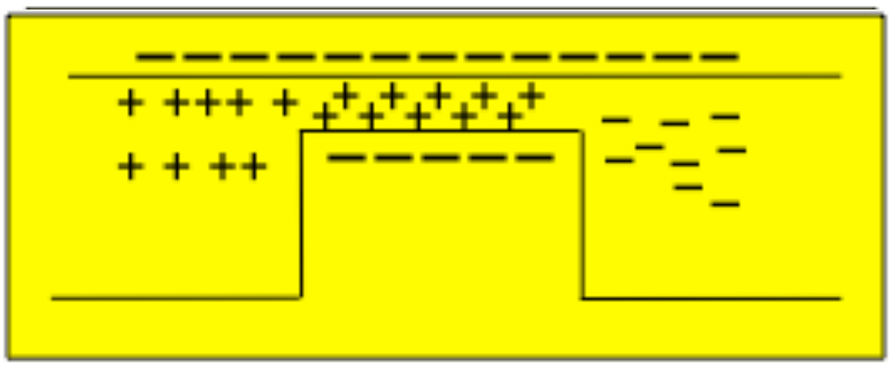
$$\lambda_D = \sqrt{\frac{\varepsilon RT}{2F^2 c}}$$

Conc / M	λ_D / nm
10^{-5}	100
10^{-4}	30
10^{-3}	10
10^{-2}	3
10^{-1}	1

Ref. http://www.kirbyresearch.com/index.cfm/wrap/textbook/microfluidicsnanofluidicsse51.html#x62-1920009.1

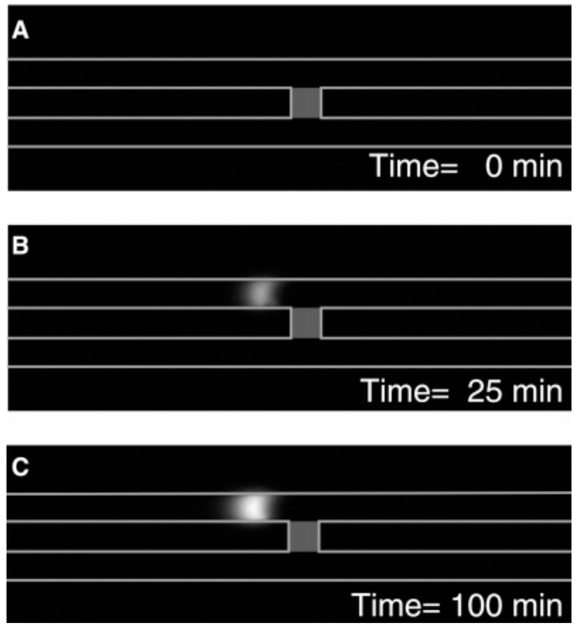
Debye layer overlapping

Field ON
Field OFF



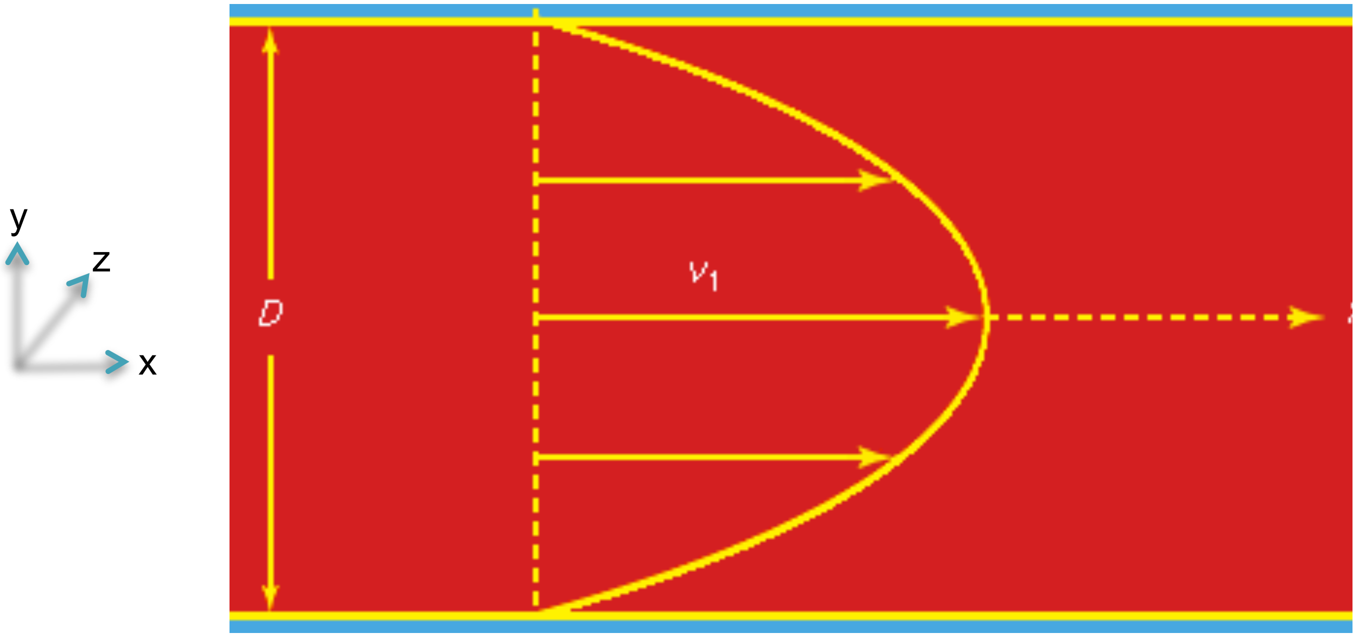
<u>Nanoconcentrators</u>

Wang et al., Anal. Chem. 2005



Pressure-driven Poiseuille Flow (parabolic)

$$v_x(y) = \frac{1}{2\eta}\frac{\Delta p}{l_x}[(a/2)^2 - y^2]$$



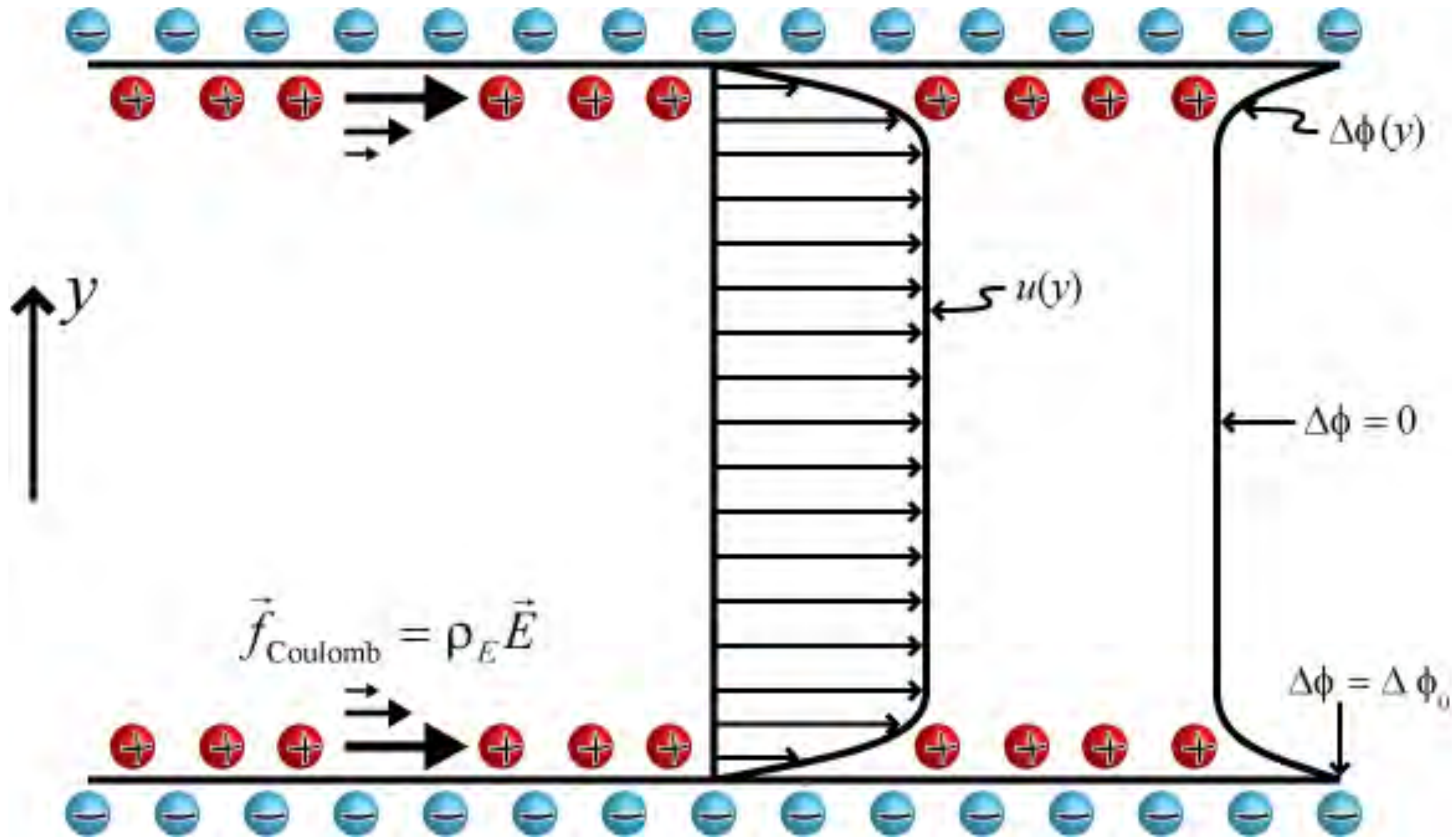
Ref. Lecture Notes on Micro/nanofluidics

Electrical double layer and electroosmotic flow

$$f_{\mathrm{DEP}} = 2\pi r_{\mathrm{p}}^{3}\varepsilon_{\mathrm{m}}\, Re(f_{\mathrm{CM}})\nabla E^{2}$$

"Plug flow"

$$f_{\mathrm{EK}} = -6\pi\eta r_{p}\mu_{\mathrm{EK}} E$$



http://www.kirbyresearch.com/index.cfm/wrap/textbook/microfluidicsnanofluidicsch6.html

Electroosmosis flow

Electroosmotic mobility: $\vec{v}_{Surface,wall} = \mu_{EO} \vec{E}_{ext,wall}$

WALL MATERIAL	SOLUTION	μ_{EO}
glass	pH7, 1 mM NaCl	3×10^{-8} m²/V s
glass	pH5, 1 mM NaCl	1×10^{-8} m²/V s
silicon	pH7, 1 mM NaCl	3×10^{-8} m²/V s
poly(dimethylsiloxane)	pH7, 1 mM NaCl	1.5×10^{-8} m²/V s
polycarbonate	pH7, 1 mM NaCl	2×10^{-8} m²/V s

$$\mu_{EO} = -\frac{\varepsilon\varphi_o}{\eta}$$

Electrokinetic potential or zeta potential: $\zeta = -\frac{\mu_{EO}\eta_{bulk}}{\varepsilon_{bulk}}$

ζ is an experimentally observed quantity that has units of *volts*. If the fluid has uniform ε and η, then the measured ζ is equal to ϕ_o. *If the fluid permittivity or viscosity vary in the electrical double layer, then a different integral analysis must be performed to relate* ζ *to* ϕ_o.

Steering of particles by Electroosmotic Actuation

M.Armani, S.Chaudhary, R.Probst, B.Shapiro (U. Maryland)

Exercise (due 1/5/2011)

- E. coli coasting time and distance? Assume radius is 1 micrometer, velocity 30 um/s.
- Diffusion (random walk) which is not Gaussian? Give an example. (Steve Granick).
- Describe an experimental technique which is capable of measuring zeta potential.