Integrated Nanofluidic Devices and Circuits

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Scales

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Reynolds Number, Re = UD/ν

10^{7} m

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

10^{5} m

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

10^{2} m

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

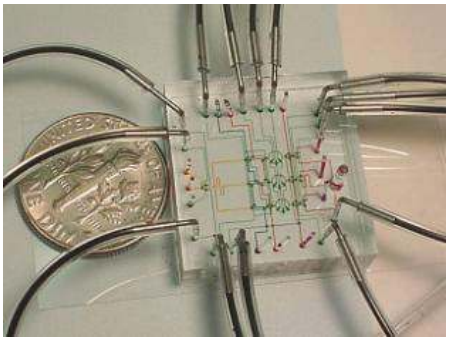
10^{-2} m

10^{-5} m

10^{-8}, 10^{-10} m

Microfluidics Innovations

Integrated Circuits



S. Quake (Caltech/Stanford)

Mixing

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

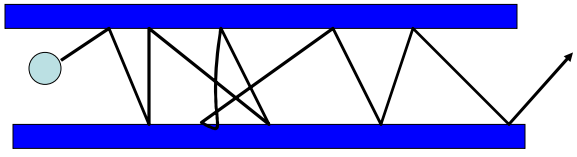
R. Ismagilov (U. Chicago)
J. Cate, A. Majumdar (UC Berkeley)

Non-Continuum Air Flow

What about liquids?

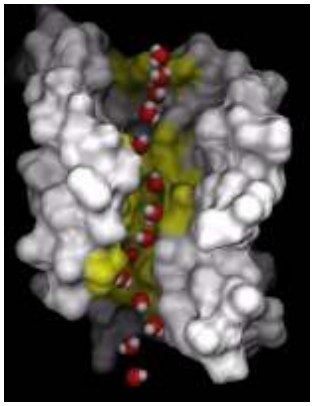
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Head Disk Spacing ~ 10 nm



Nanofluidics in Nature

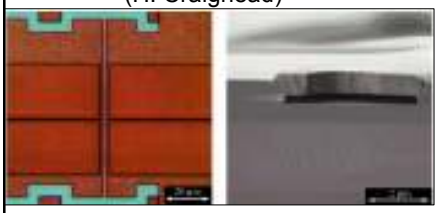
Aquaporin



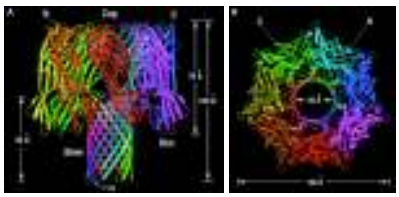
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- Discovered in 1992
- Nobel Prize in Chemistry to Peter Agre, 2003

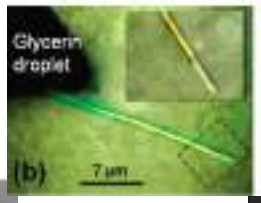
Cornell Group
(H. Craighead)



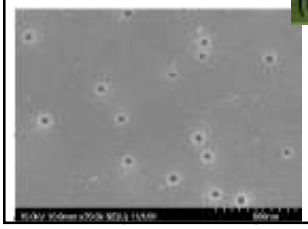
Texas A&M; NIST; Harvard; UCSC



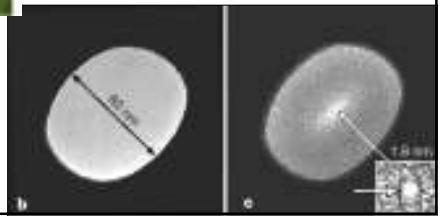
U Penn
(H. Bau)



Illinois & Florida Groups



Harvard & Purdue Groups



Length Scales

Steric Hydration

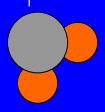
Van der Waals

Electrostatic
(In aqueous solutions)

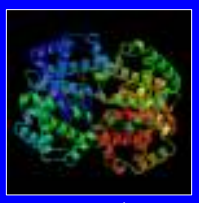
1 Å | 1 nm | 10 nm | 100 nm | 1 μm | 10 μm

Small molecules | Macro-molecules | Viruses | Bacteria, fungi, yeasts

Water molecule



Hemoglobin



www.rcsb.org

www.ericsecho.org

E. Coli bacteria

Electrostatic Interactions

- Boltzmann distribution

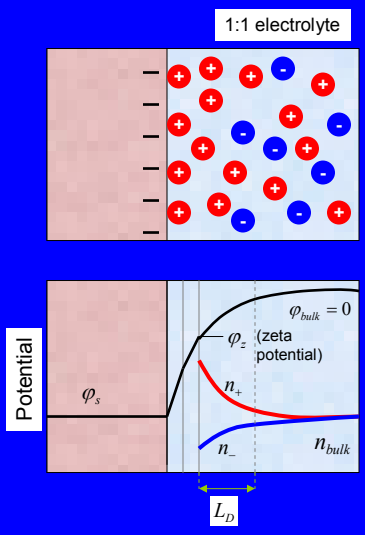
$$n_{\pm} = n_{bulk} \exp\left(\frac{\mp e\varphi}{kT}\right)$$

- Poisson equation

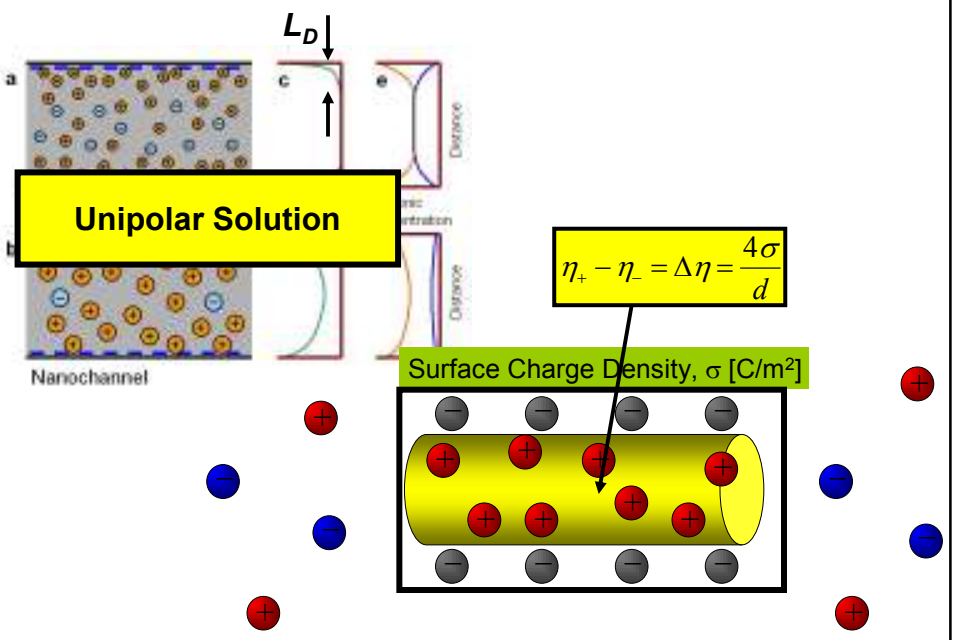
$$\nabla^2\varphi = \frac{-\rho}{\varepsilon} = -\frac{e(n_+ - n_-)}{\varepsilon}$$

- Debye length

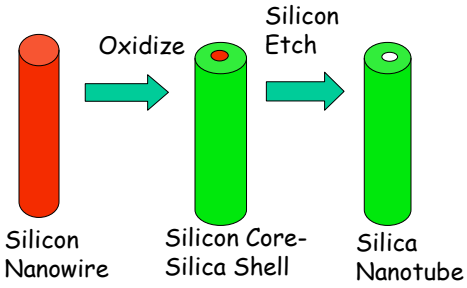
$$L_D = \sqrt{\frac{\varepsilon kT}{2n_{bulk}e^2}} \quad (1\text{-}100 \text{ nm})$$



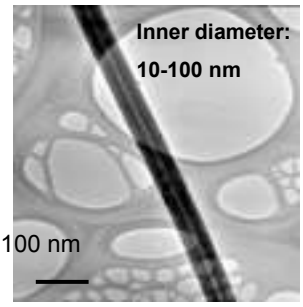
Confined Ions

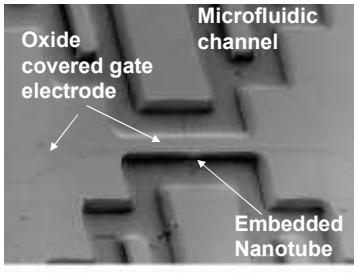


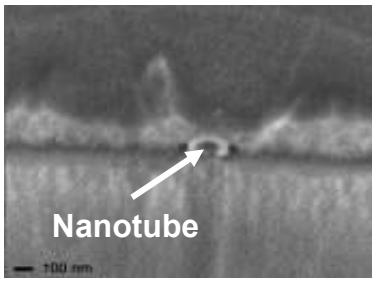
Nanotube Fluidics



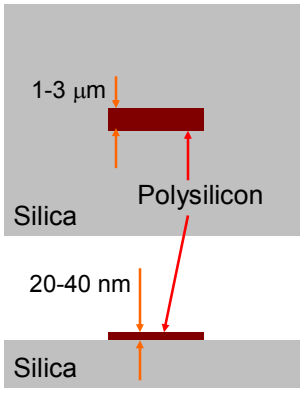
Fan, Li, Majumdar, Yang, JACS'03



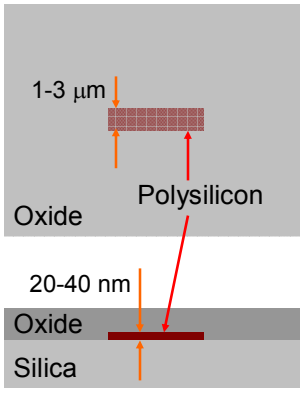




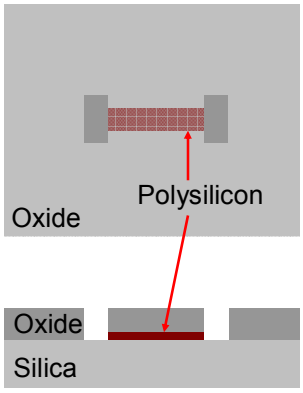
Fabrication Scheme



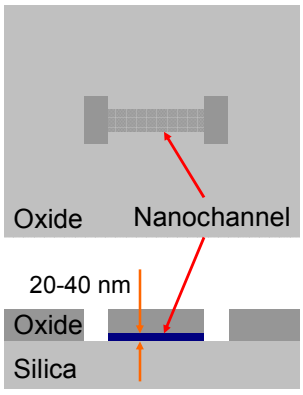
Fabrication Scheme



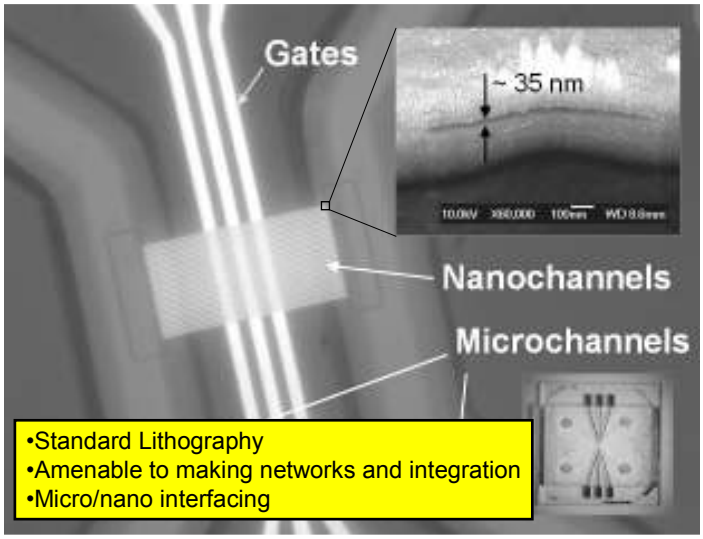
Fabrication Scheme



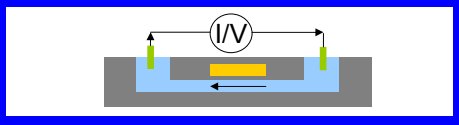
Fabrication Scheme

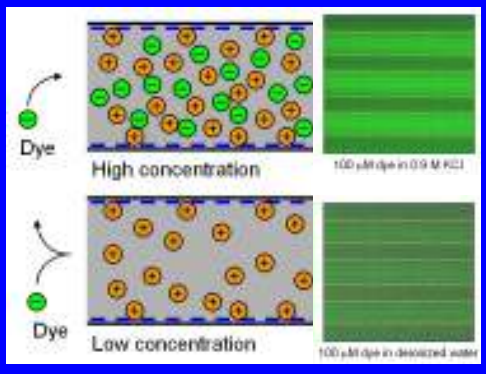


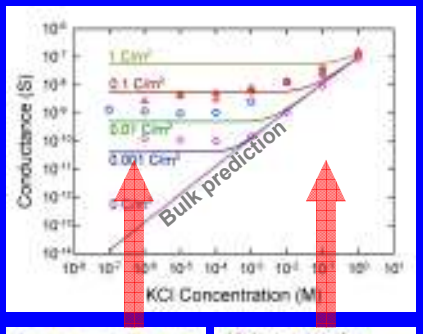
Nanochannel Device

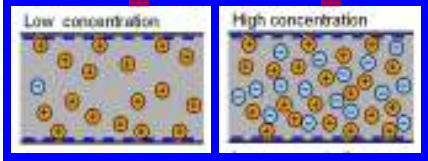


Signatures of Unipolar Solution





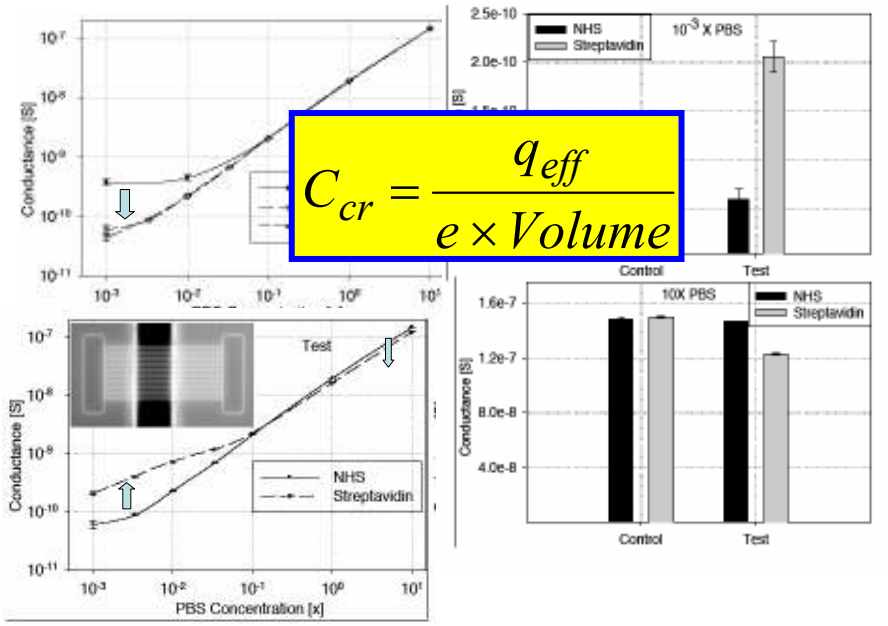




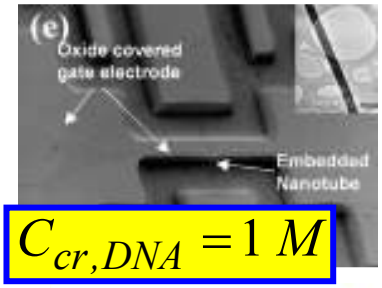
Dye used: Alexa Fluor® 488 cadaverine, sodium salt

Surface Reactions

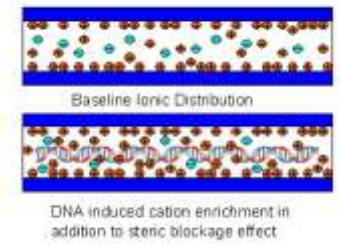
$$C_{cr} = \frac{q_{eff}}{e \times Volume}$$

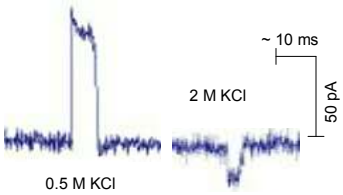


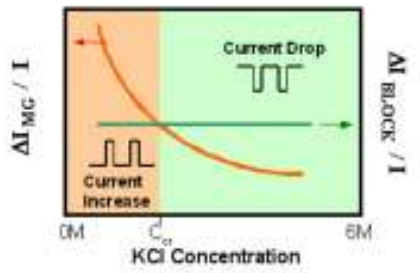
Single Molecule Transport



$$C_{cr,DNA} = 1\ M$$

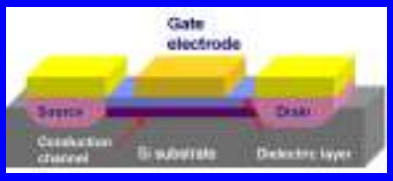




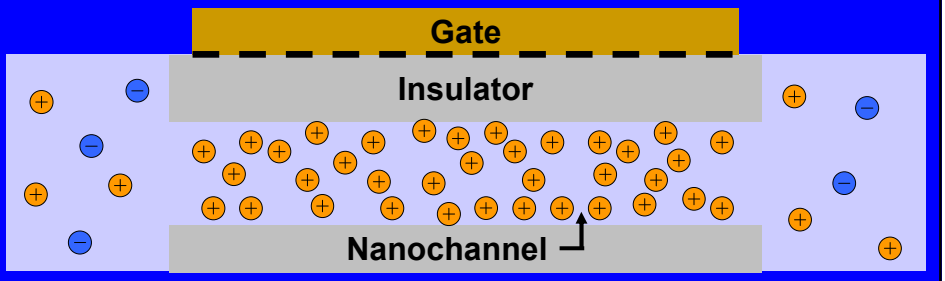


Nanofluidic Transistor

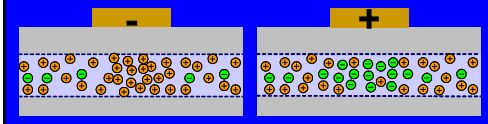
Debye length ~ channel height

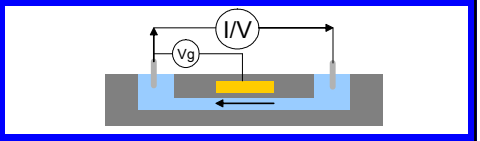


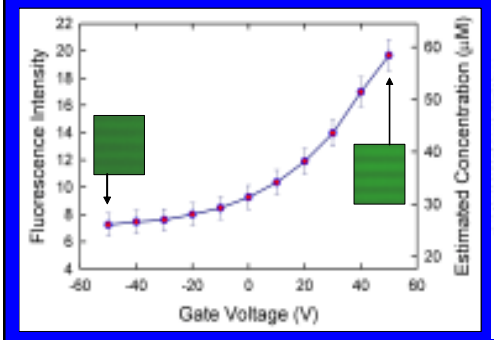
MOSFET

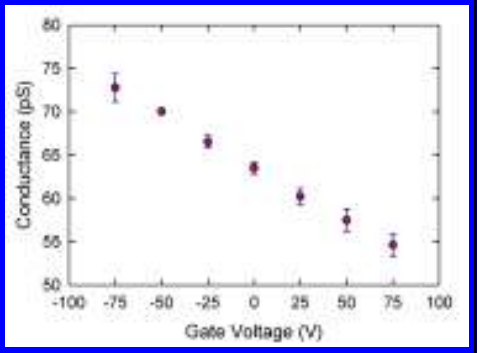


Field-Effect Flow Control









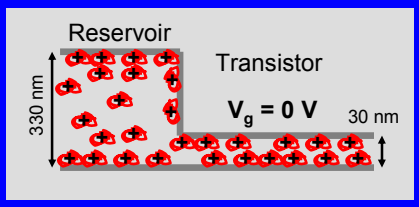
Dye used: Alexa Fluor® 488 cadaverine, sodium salt, 100 μM in deionized water

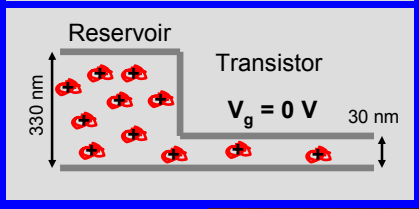
Conductance measurements: 100 μM KCl in deionized water

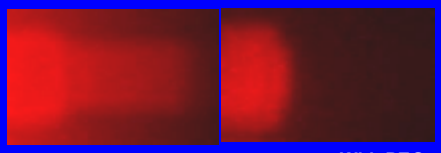
Karnik, Fan, et al. *Nano Lett.* (2005)

Control of Protein Transport

- Highly surface-active
  - Structural rearrangements
  - Hydrophobic interactions
  - Electrostatic interactions
- Field-effect control
  - Protein-repellant
  - Electrically neutral
    - Poly(ethylene glycol) (PEG)
    - Epoxy-silane + Ethanolamine



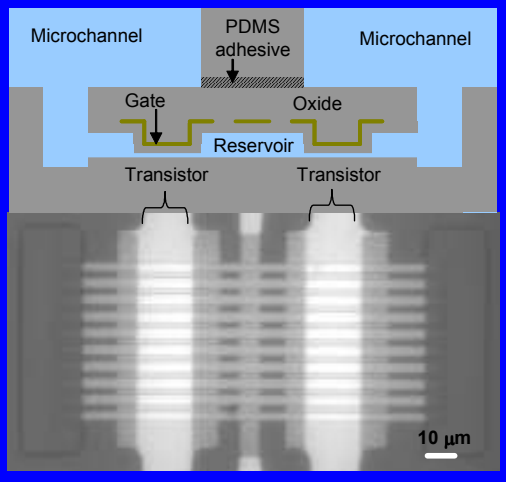




Adsorption With PEG

30 μM Alexa 488 avidin in 10 μM KCl

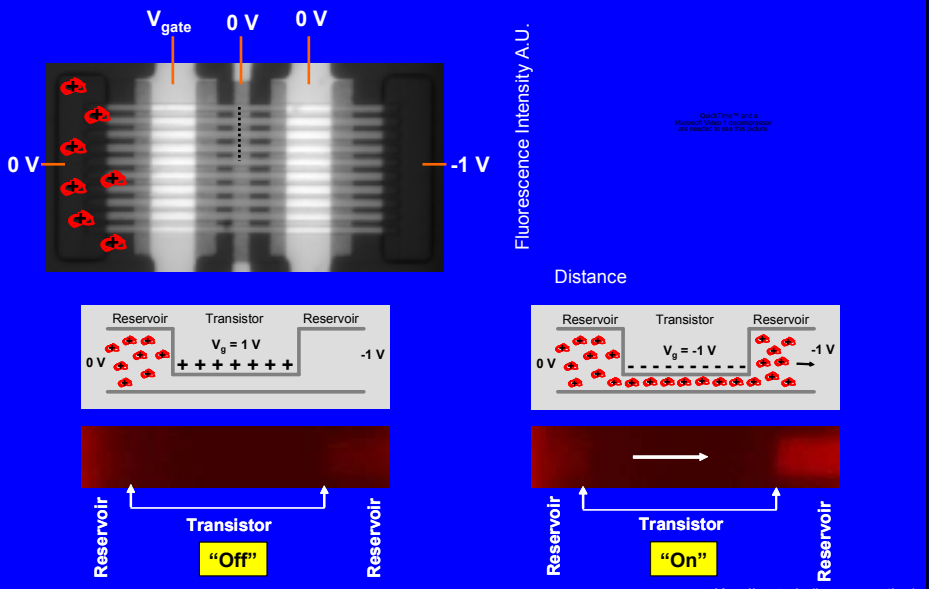
Control of Protein Transport



30 μM Alexa 488 avidin in 10 μM KCl

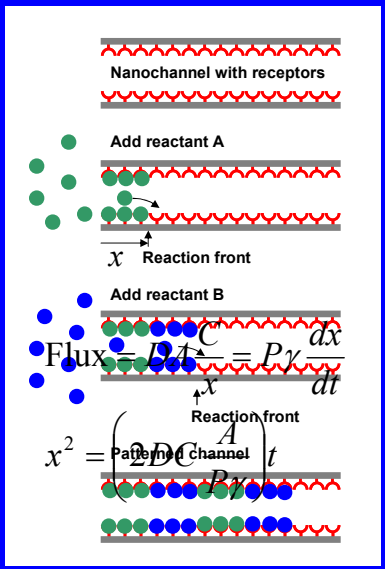
Karnik, et al. APL (2006)

Protein Flow Control



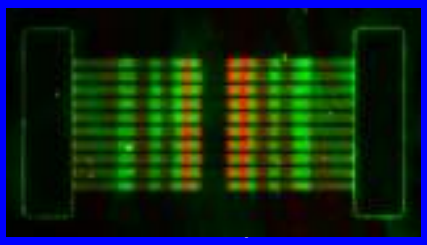
Karnik, et al. *(in preparation)*

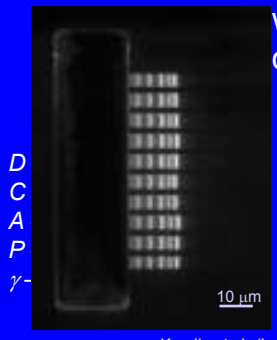
Molecular Patterning



$$\text{Flux} = -D\frac{\Delta C}{x} = P\gamma\frac{dx}{dt}$$

$$x^2 = \left(\frac{2DC}{P\gamma}\frac{A}{}\right)t$$

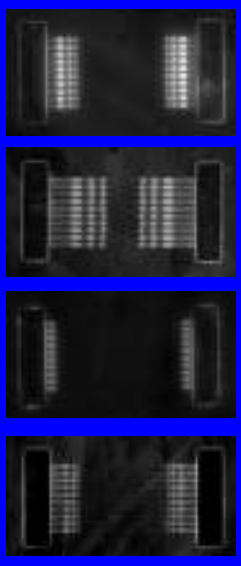




with dyes

Karnik, et al. *(in preparation)*

Molecular Patterning

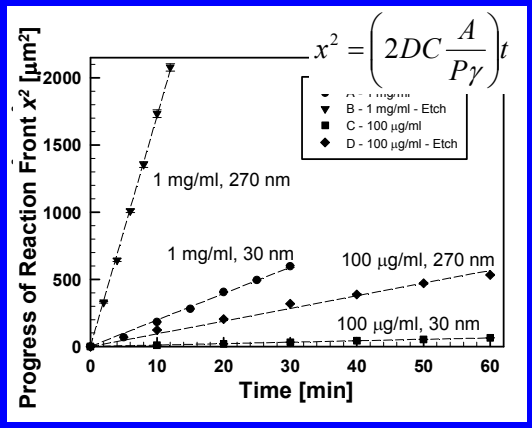


A
1 mg/ml
30 nm channel

B
1 mg/ml
~270 nm channel

C
100 μg/ml
30 nm channel

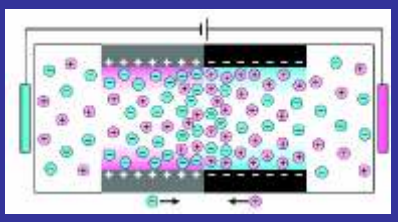
D
100 μg/ml
~270 nm channel



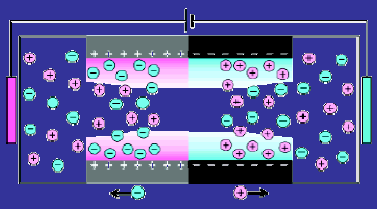
Patterning of molecules
Patterning of surface charge

Karnik, et al. *(in preparation)*

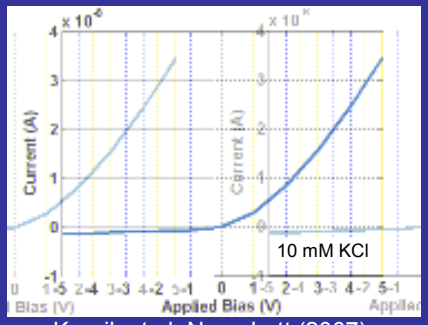
Rectification of Ionic Transport: Diode



Forward bias- Enhancement



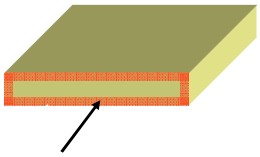
Reverse bias- Depletion
Daiguji et al. Nano Lett. (2005)



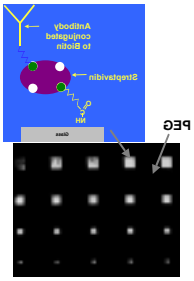
Karnik et al. Nano Lett (2007)

On-Going Work

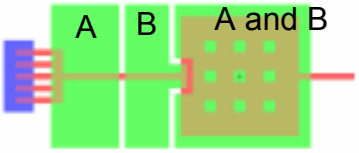
❑Surface Chemistry



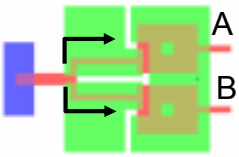
Covalently Bonded
PEG, DNA, or proteins



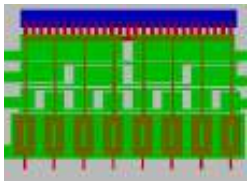
❑Device Design



AND Gate



Sorter



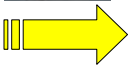
3-Bit
Multiplexer

Systems Concept

Digital Electronics

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Electronic
Transistor

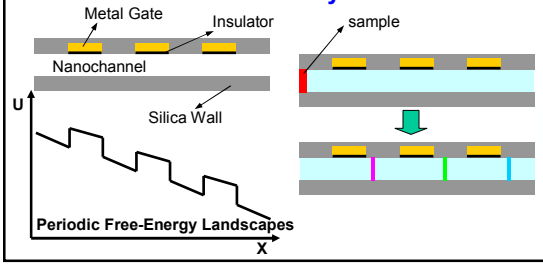


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

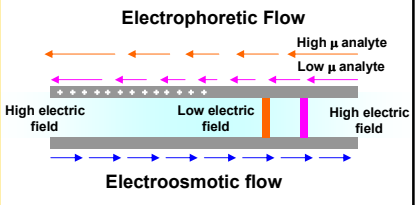
Integrated circuits
for processing
electronic
information

Programmable Molecular Router

Molecular Sieving in Nanofluidic Transistor Array

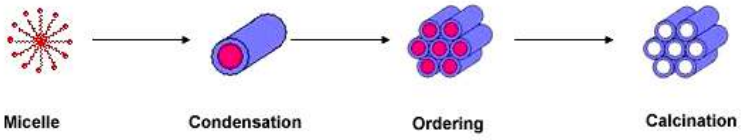


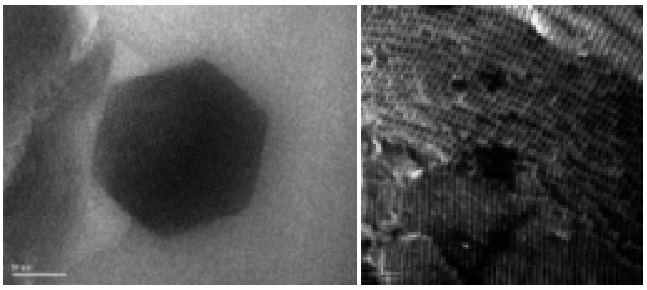
Electric Field Gradient Focusing in Nanofluidic Diode



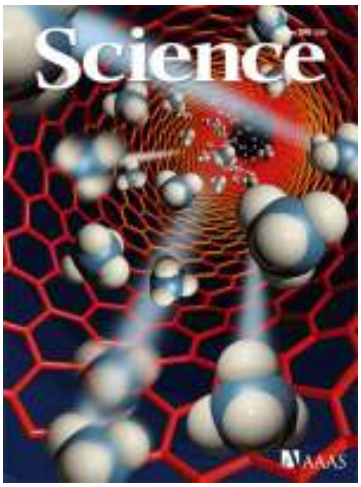
Using Diode to create electric field gradient

Future Work





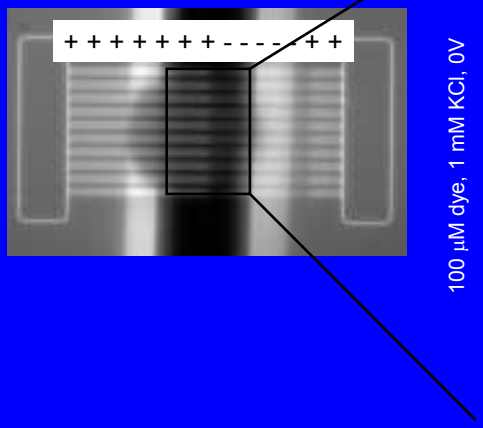
1-2 nm nanotubes



Gas and liquid flow in sub-2 nm carbon nanotube membrane

Holt et al., *Science* **312**; 1034 - 1037 (2006).

And then there are surprises…



100 μM dye, 1 mM KCl, 0V

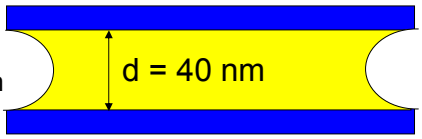
QuickTime™ and a
H.264 decompressor
are needed to see this picture.

100 μM dye, 1 mM KCl, 10V

More Surprises!!

Evaporation

Surface Tension: σ = 0.07 N/m



Capillary Pressure

$P_c \sim \sigma/d \sim 10$ atm

Water

Acetone

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H.264 decompressor
are needed to see this picture.

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H.264 decompressor
are needed to see this picture.