Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 10: Microfluidic Devices: Concept and Applications

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What is Microfluidics?

• Microfluidics is a technology which refers to the research and development of micro-scale devices which handle small volumes of fluids (as small as micro-, nano-, pico- and even femtoliter volumes).

• The devices have dimensions ranging from several millimeters to micrometers ~ the miniaturization of the entire system is not a requirement.

• Materials for microfluidics
• Fabrication of microfluidics
• Microfluidic components

Microfluidics

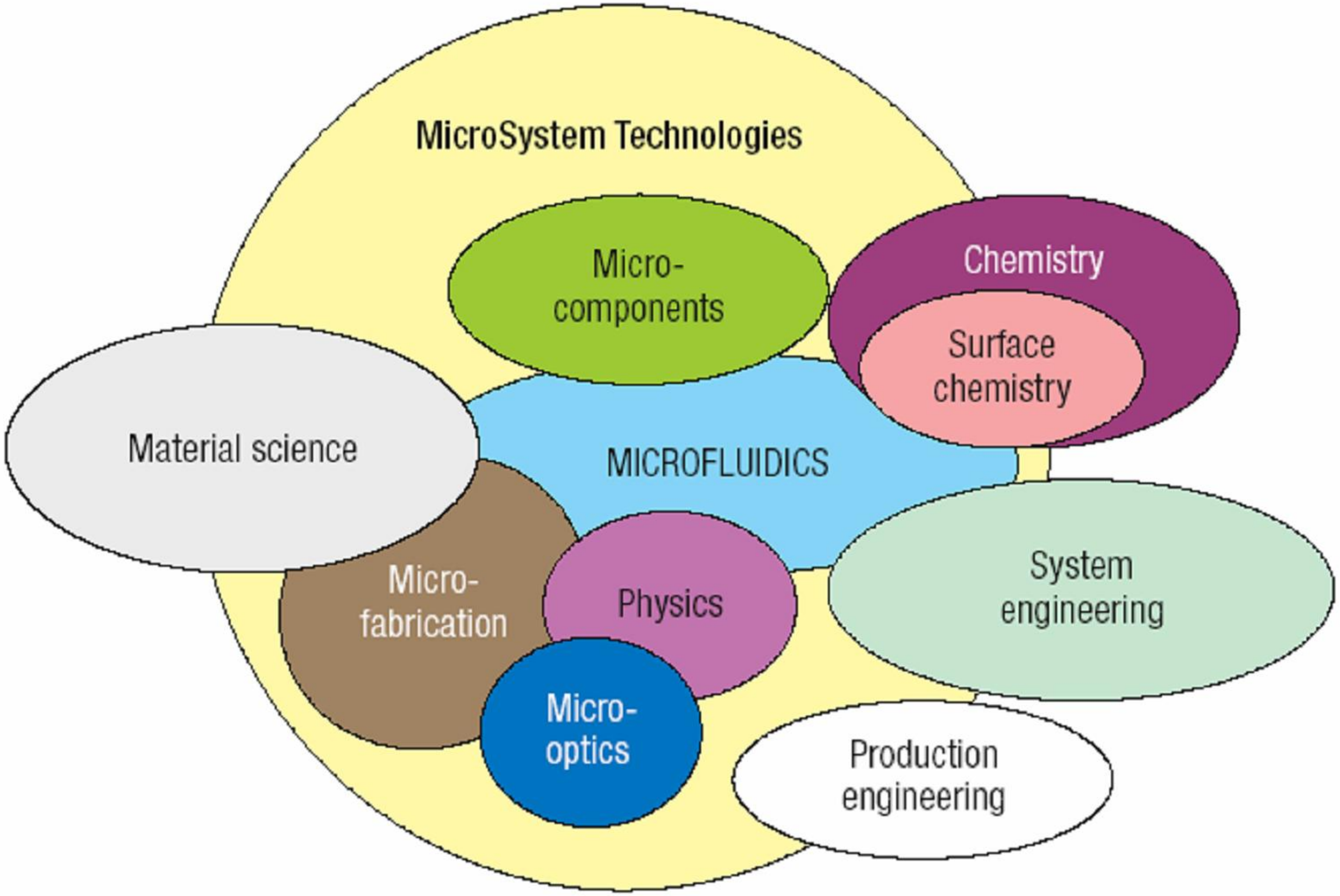


Figure 1. Microfluidics and related areas of science and engineering.

Microfluidics (Con't)

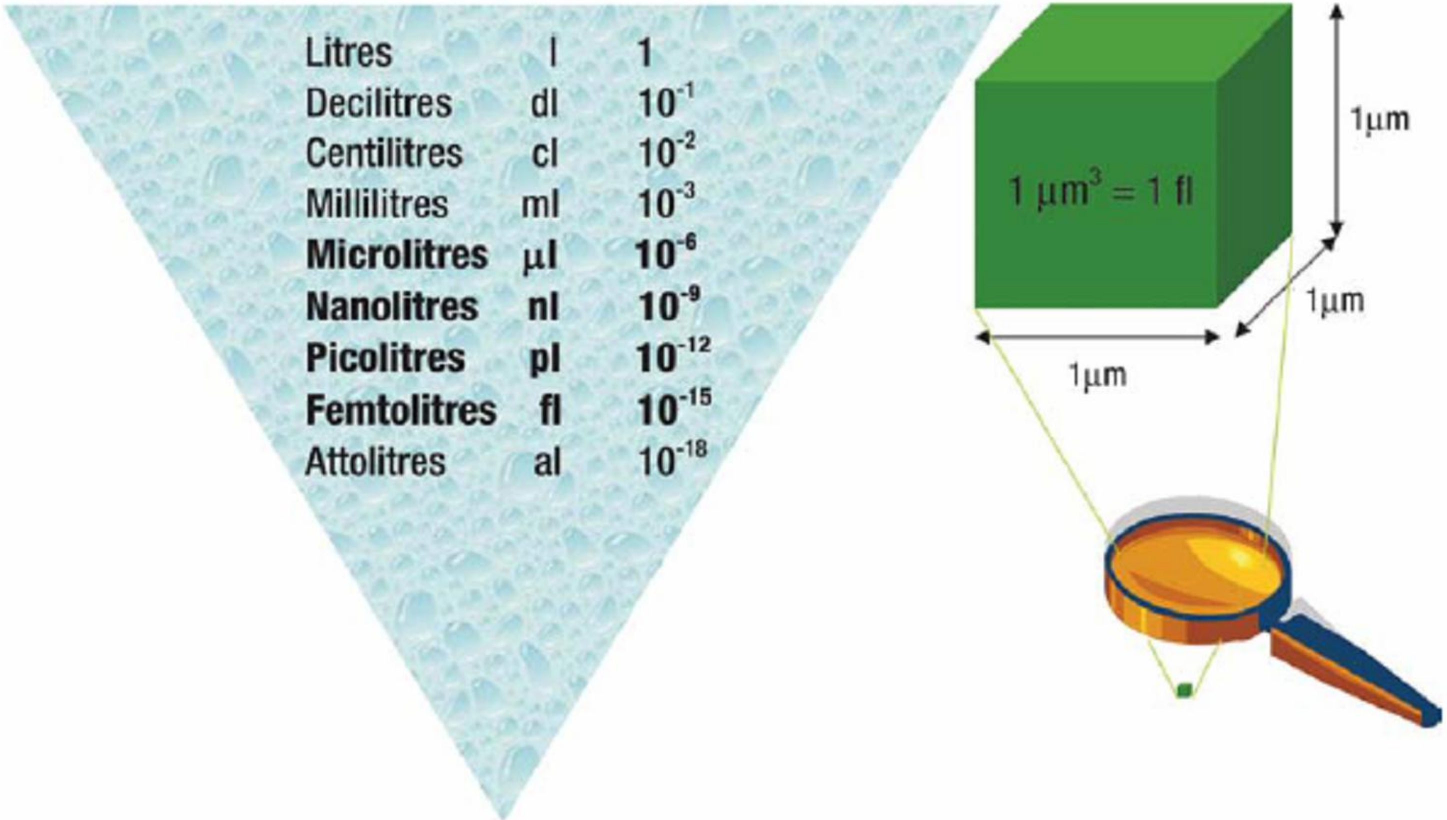


Figure 2. Downscaling of volumes.

Materials for Microfluidics

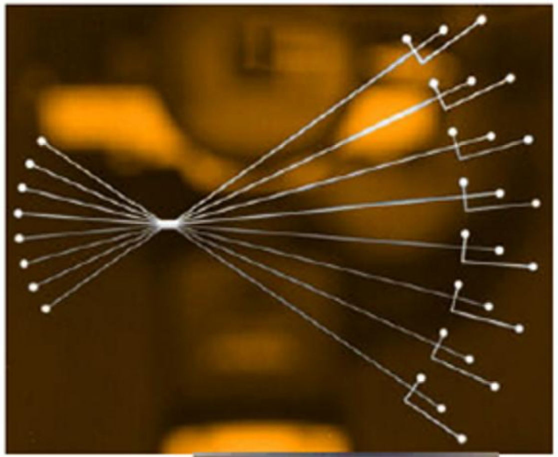
	Silicon	Glass	Mylar	PDMS
fabrication	etching	etching	laser cutting	molding
optical	opaque	transparent	transparent	transparent
structure	rigid	rigid	'rigid'	elastomeric
bonding	anodic	thermal	thermal	self-sealing
permeability	-	-	-	organics, gasses
pumping	pressure	EOF	pressure	EOF

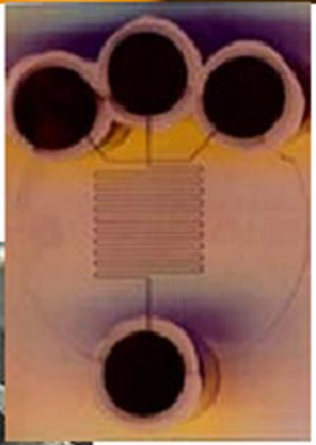
Material of choice depends on:

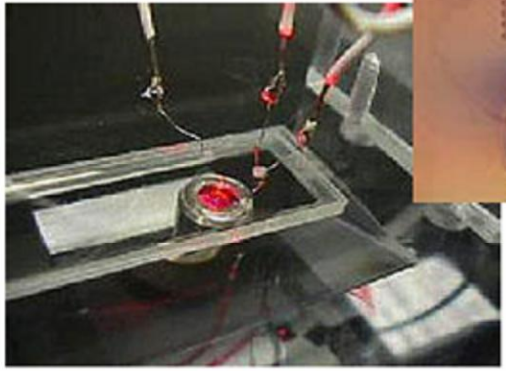
- **Application**
- **Prototyping vs. Mass production**

Advantages of Microfluidics

- smaller volumes -- less reagent/sample consumption
- shorter analysis time
- increased throughput -- parallel analysis
- increased automation
- improved integration of sample steps
- easier fabrication







Applications of Microfluidics

- Diagnostics: point of care analysis, total analysis systems
- Pharmaceutics: drug delivery, drug testing
- Medical: drug delivery, in vivo diagnostics
- Food industry: food diagnostics, packaging (smart sensors)
- Biotechnology: DNA chips, protein chips, cell chips
- Chemistry: analytical (lab-on-a-chip), production (microreactor)
- Process industry: process control, on-line measurements
- Environmental technology: soil, water, and air quality control
- Automobile industry: fuel injection, oil quality monitoring, exhaust gas analysis and others
- Consumer electronics: ink-jet printers, local cooling of electronics, fluidic power systems, well being, etc.

Resources on Microfluidics

More information about the various aspects of microfluidics can be found on the following microfluidics websites:

- MIFLUS – Microfluidics portal in Finland
  http://www.tut.fi/miflus

- LICOM – The Liquid Handling Competence Center
  http://www.microfluidics.de/

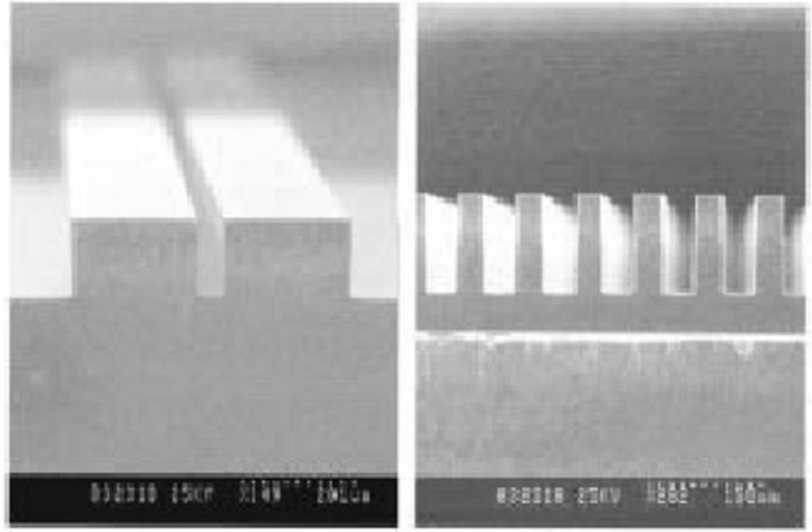
- FLOW MAP: Microfluidics Roadmap
  http://www.microfluidics-roadmap.com/

- myFLUIDIX.com: a microfluidics web course
  http://www.myfluidix.com/

Microfluidic channels

- Variety of shapes and manufacturing techniques, depending on application.

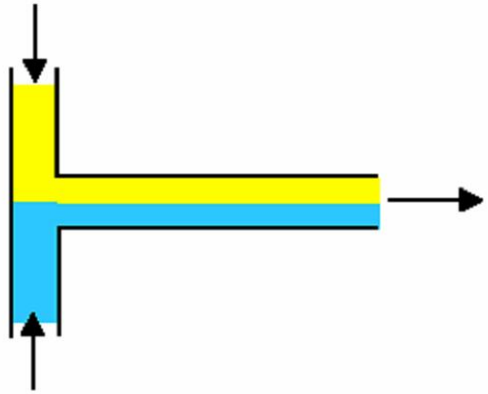
- Typically laminar due to very small length scales and flow rates.



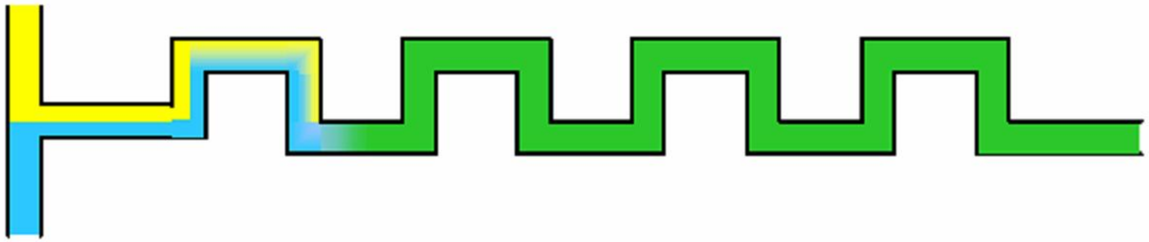
$$\mathrm{Re}_{D,\max} = \frac{UD_h}{\nu} \approx \frac{\left(10\,{}^{mm}\!/_{s}\right)\left(500\,\mu m\right)}{1\,{}^{mm^2}\!/_{s}} = 5$$

Mixing in Microfluidics

Problem: laminar flow



Passive Solution: bends and turns



Active Solution: induce chaos via pumping, movement

Laminar Flow in Microfluidic Channels

$$Re = \frac{l.v.\rho}{\eta}$$

l = diameter channel (m)
v = flow velocity (m/s)
? = density (g/m^3)
? = viscosity (Pa.s or kg/m.s)

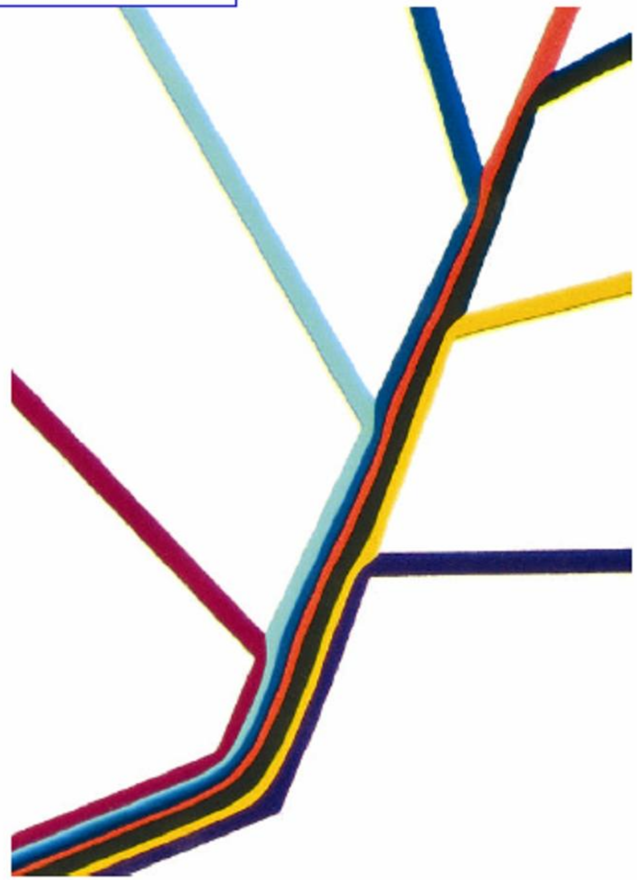
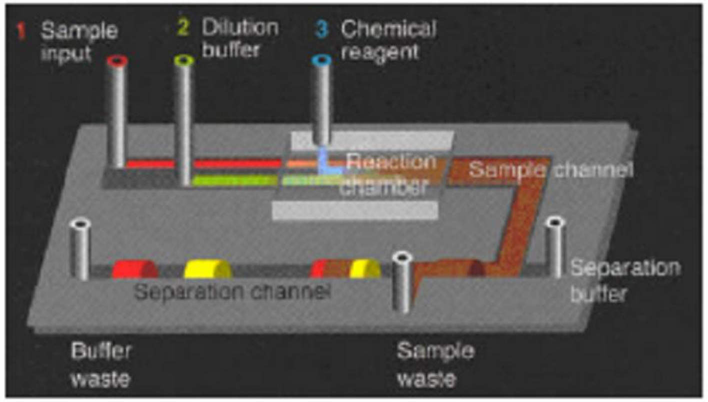


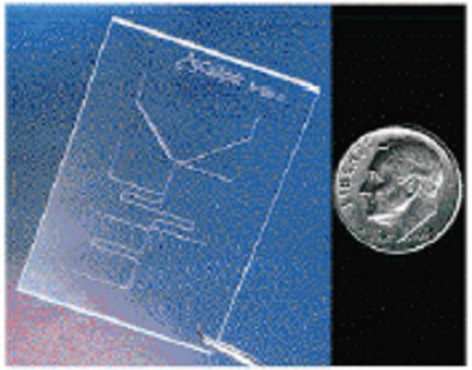
Image: Felice Frenkel

Microfluidic Systems

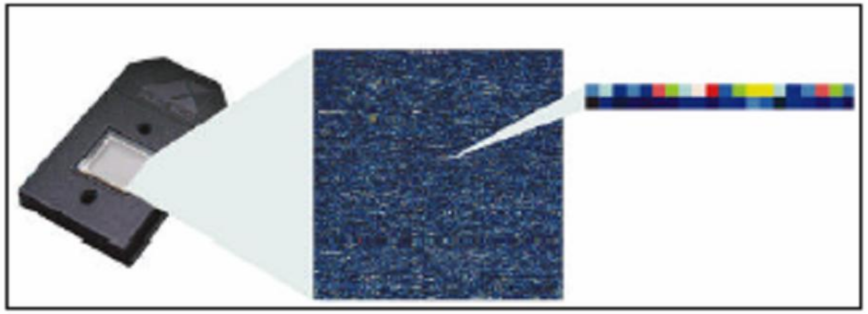
micro total analysis systems (μTAS)
high-throughput chemical screening
biological assays
chemical/biological warfare detection
point-of-care testing
chemical synthesis



Harrison (U. Alberta)



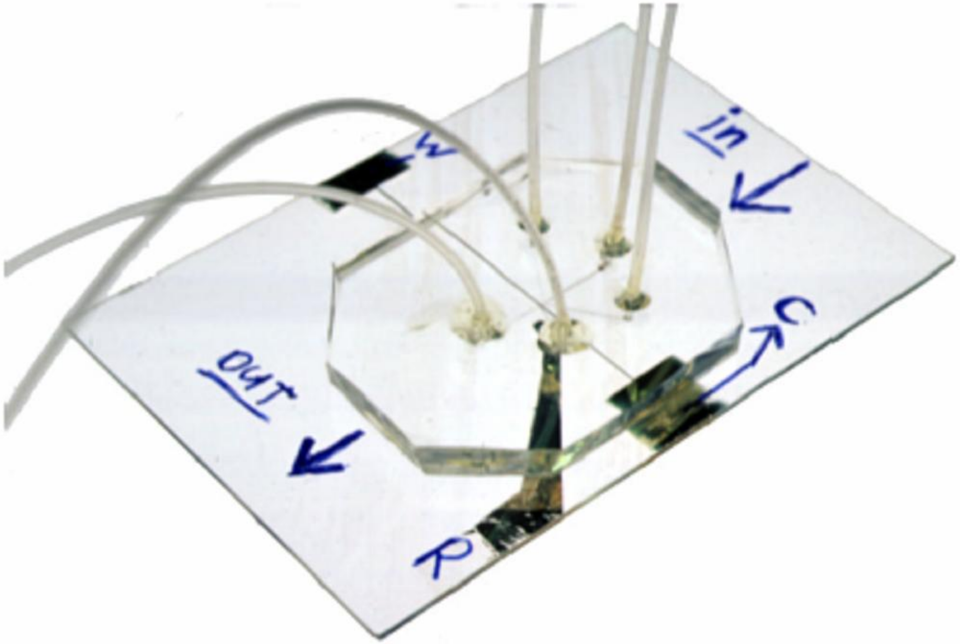
Lab-on-a-chip (Caliper)



GeneChip (Affymetrix)

PDMS-Based Microfluidics

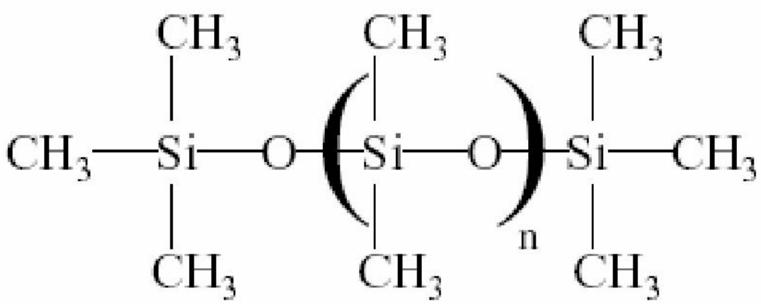
PDMS-Based Microfluidic Channels



Courtesy of P. Kenis

PDMS-Based Microfluidics (Con't)

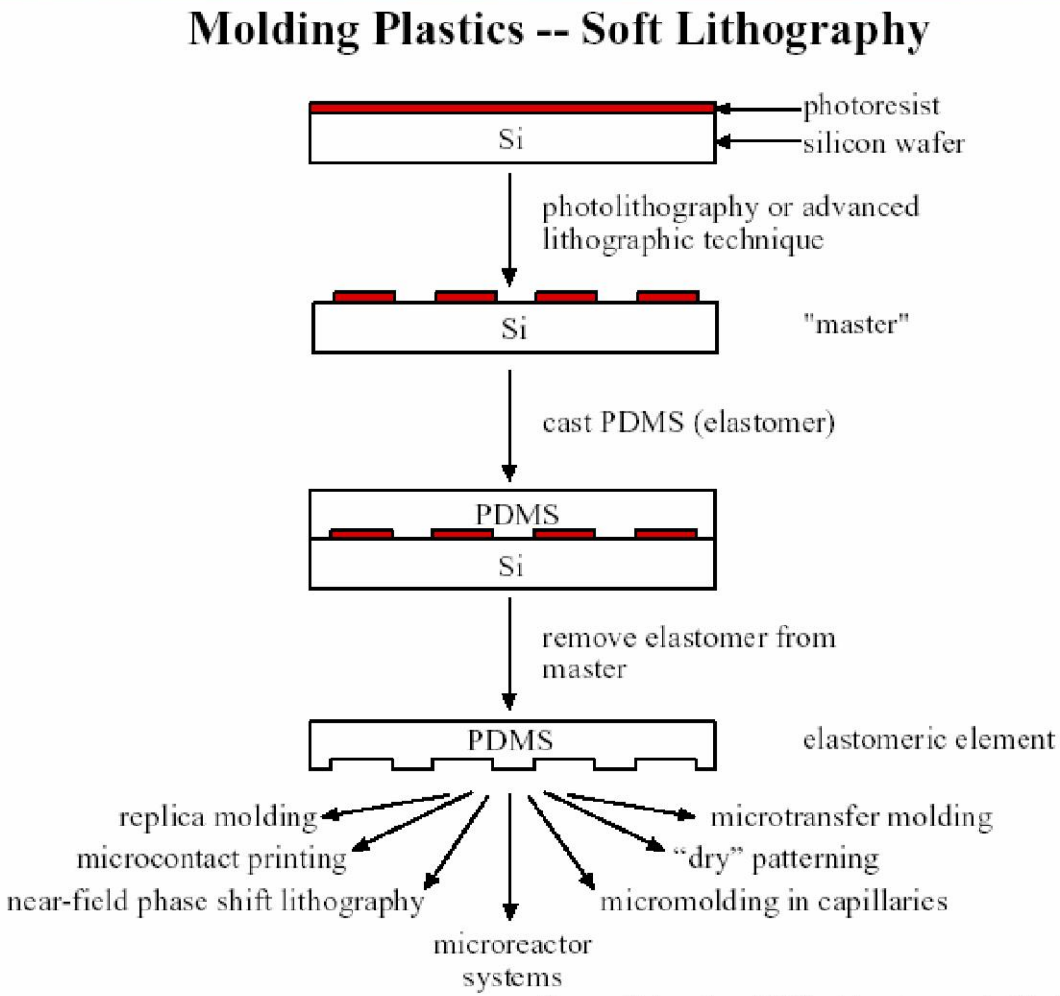
Polydimethylsiloxane (PDMS) -- A Moldable Elastomer



Properties
- moldable
- deformable
- chemically unreactive
- hydrophobic
- transparent in uv-vis
- insulating

Applications
- sealants
- adhesives
- protective coatings
- biomedical uses
- electrical potting
- microfluidics / microchemical reactors

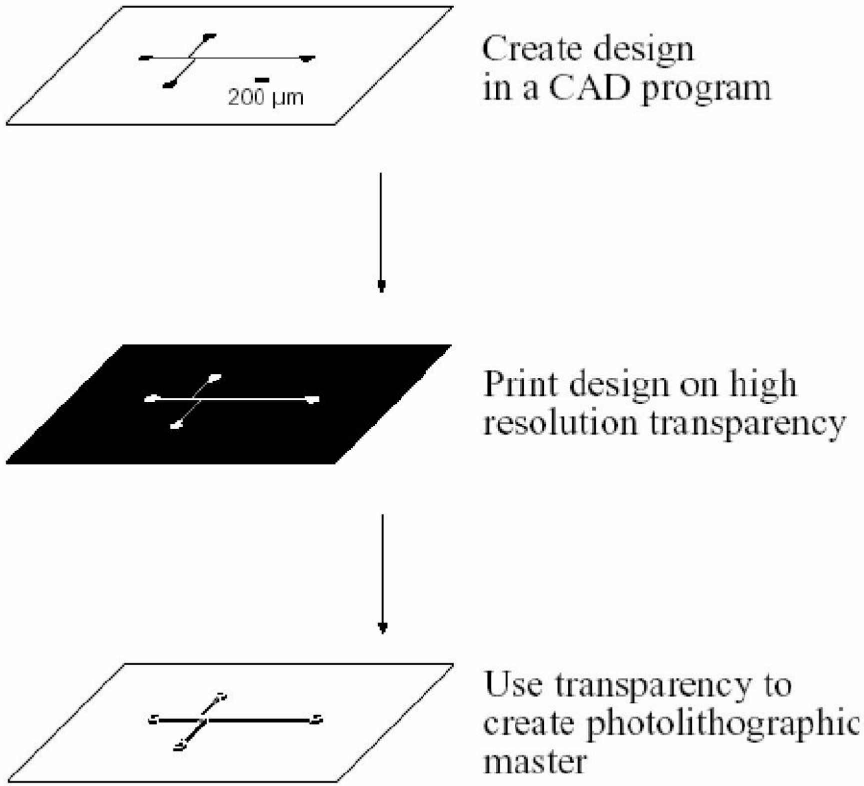
PDMS-Based Microfluidics (Con't)



Kumar, Biebuyck and Whitesides, *Langmuir*, **10**, 1498 (1994).
Xia and Whitesides, *Angew. Chem. Int. Ed. Engl.*, **37**, 550 (1998).
Jackman and Whitesides, *CHEMTECH*, **29**, 18 (1999).

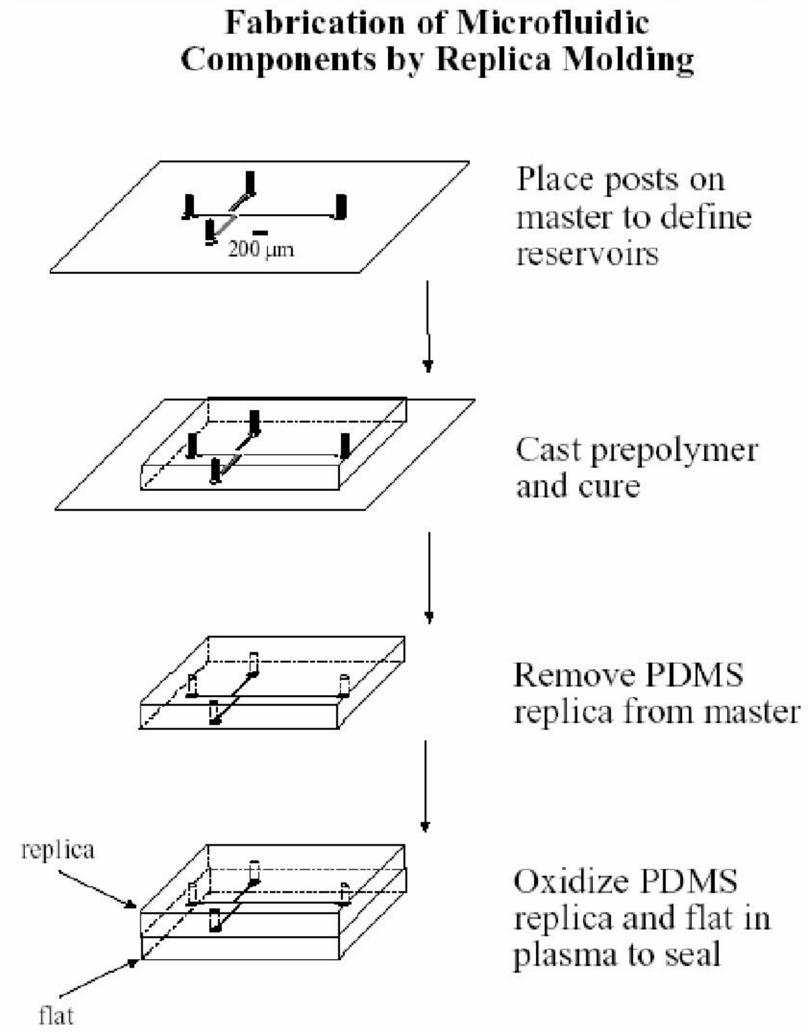
PDMS-Based Microfluidics (Con't)

Rapid Prototyping



Qin, Xia and Whitesides, *Adv. Mater.*, **8**, 917 (1996).

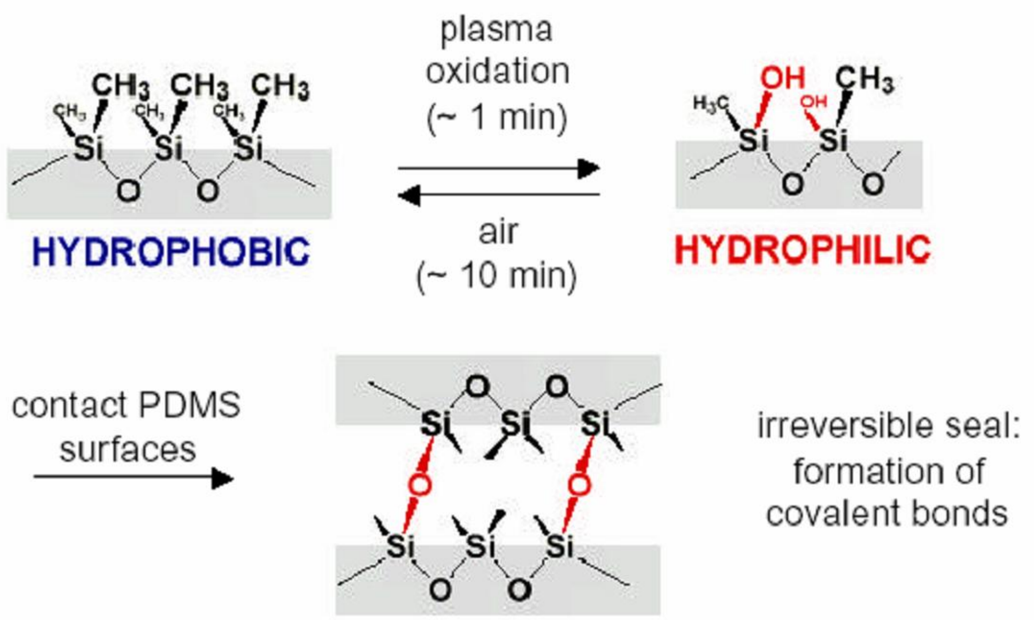
PDMS-Based Microfluidics (Con't)



Duffy, McDonald, Schueller and Whitesides, *Anal. Chem.*, **70**, 4974 (1998).

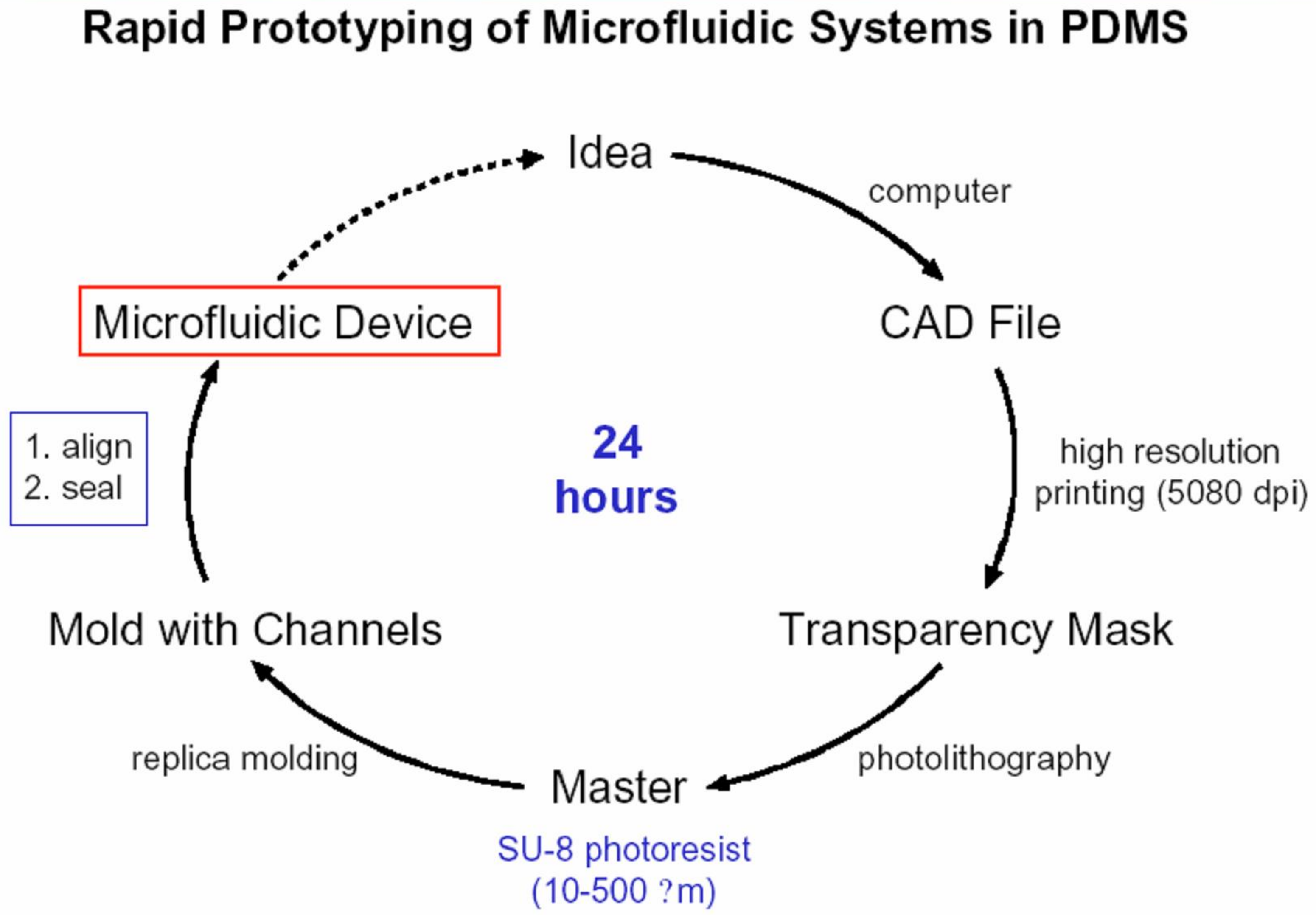
PDMS-Based Microfluidics (Con't)

Irreversible Sealing of Polydimethylsiloxane (PDMS)



- PDMS seals to itself, glass, silicon, silicon nitride, LDPE, PS
- PDMS seals after exposure to plasma of air, dry air or oxygen

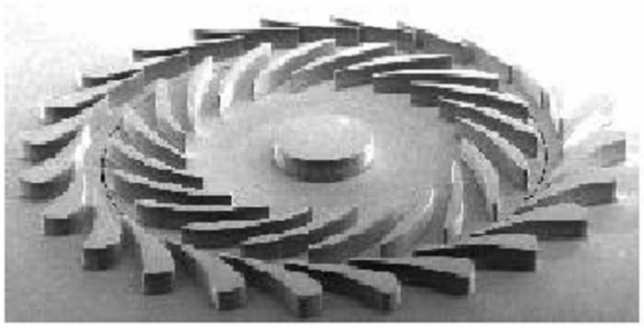
PDMS-Based Microfluidics (Con't)



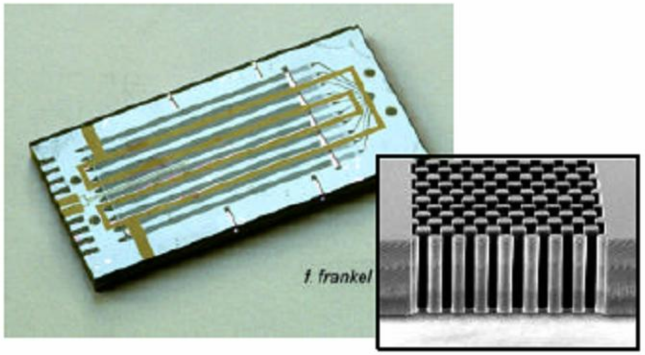
PDMS-Based Microfluidics (Con't)

Why not Silicon?

- fabrication requires regular access to a cleanroom
- processing costs can be high and cycle times long
- limited range of materials can be patterned
- only planar structures formed
- chemical compatibility, physical and optical properties can be problematic for some applications



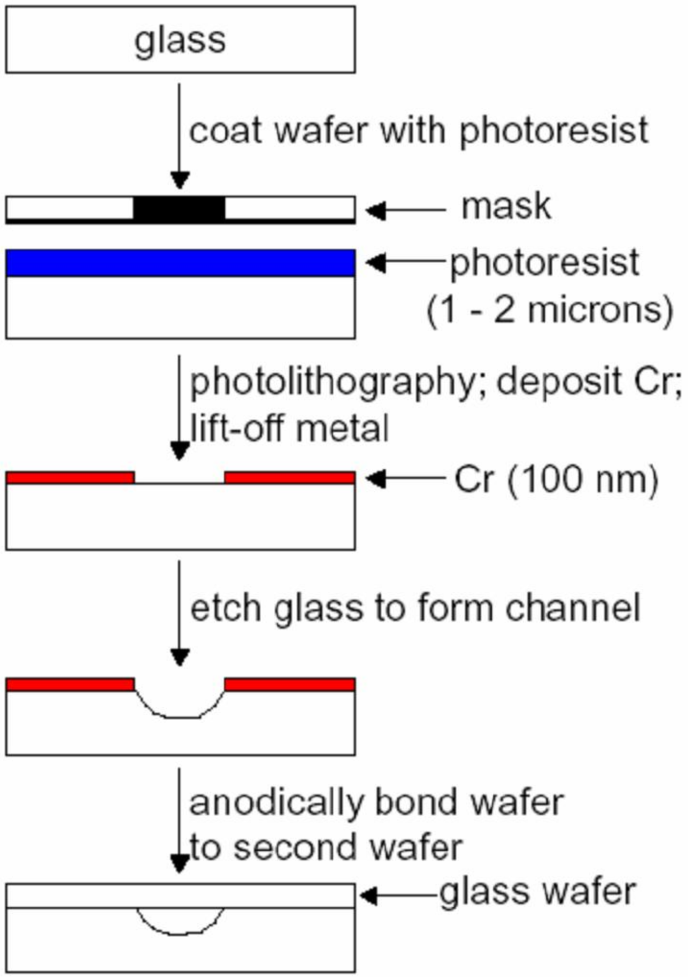
micro turbine engine (MIT)

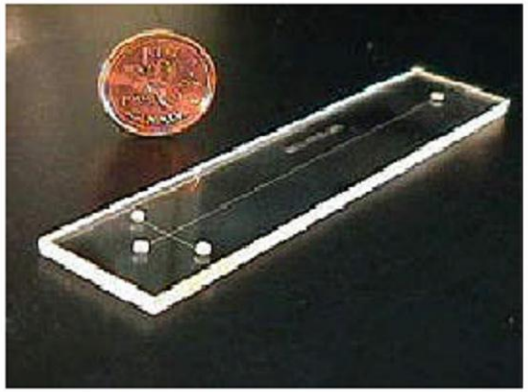


multiphase microreactor (Losey)

Glass-Based Microfluidics

Fabrication in Glass





(Source: Microlyne)

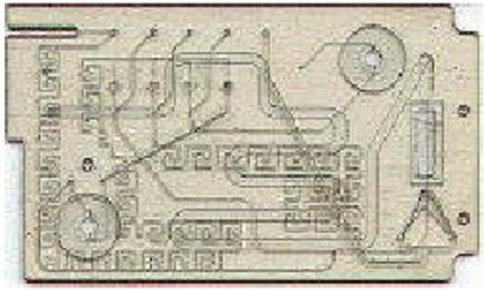
- compatible with silicon fabrication
- transparent
- insulating
- low autofluorescence
- cheaper than Si (?)

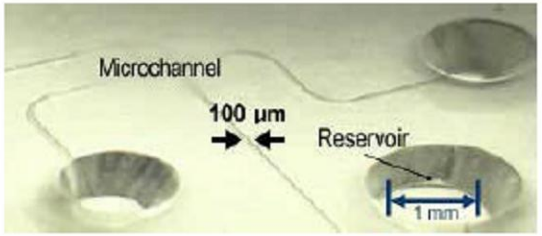
- amorphous material
- incompatible with high T

Plastics-Based Microfluidics (1)

Fabrication in Plastics...

- is cheap!
- doesn't require routine access to cleanroom
- enables single use, disposable devices
- is performed in batch

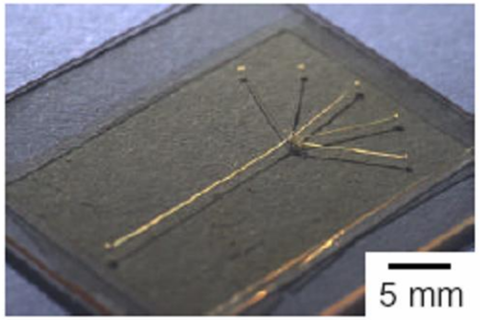


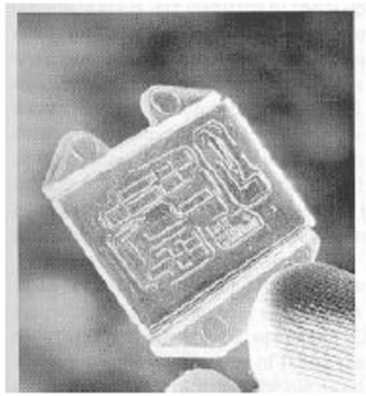


but...
can have problems with dimensional stability
some autofluoresce

Micropatterned by:

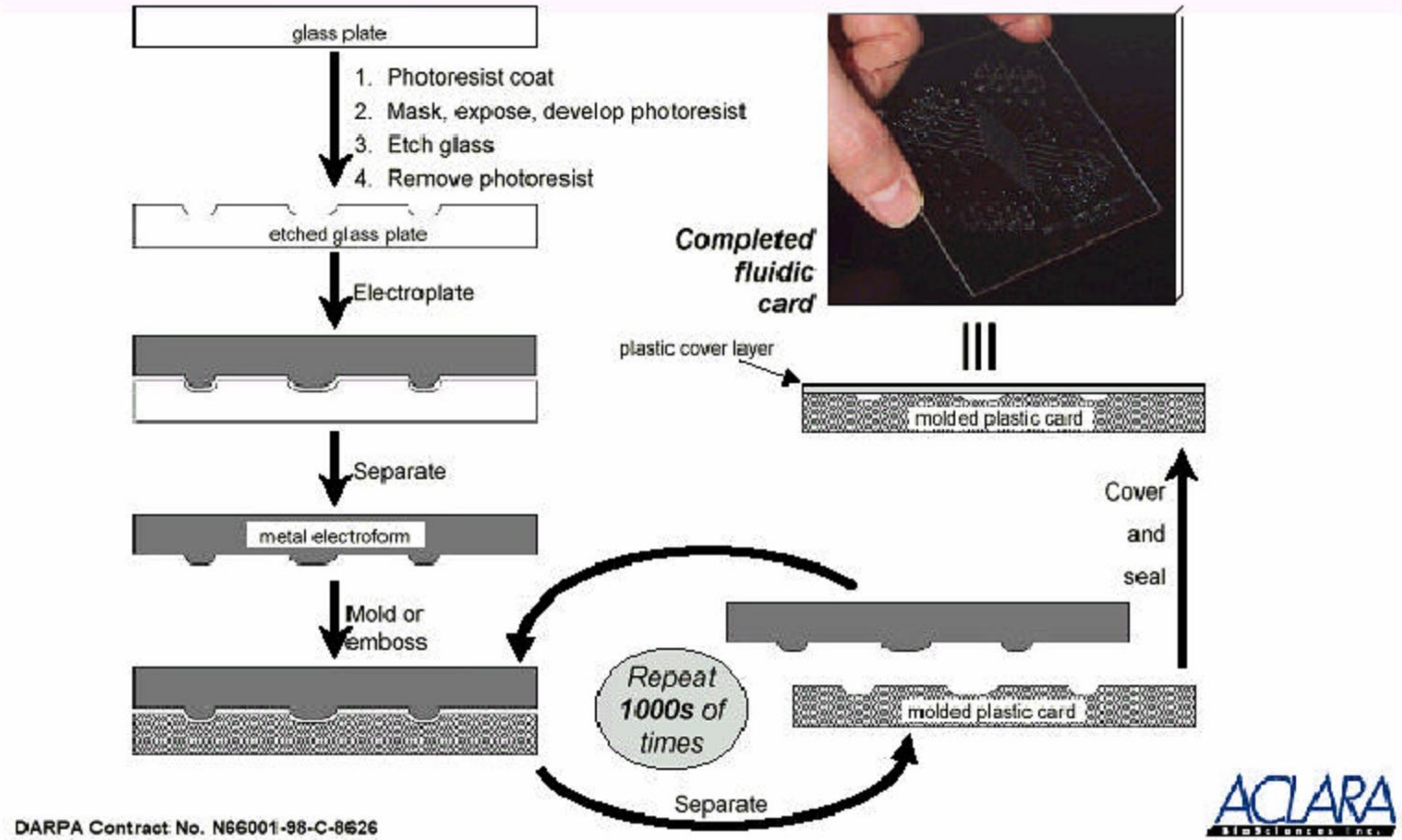
- injection molding
- embossing
- molding
- (lithography)





Plastics-Based Microfluidics (2)

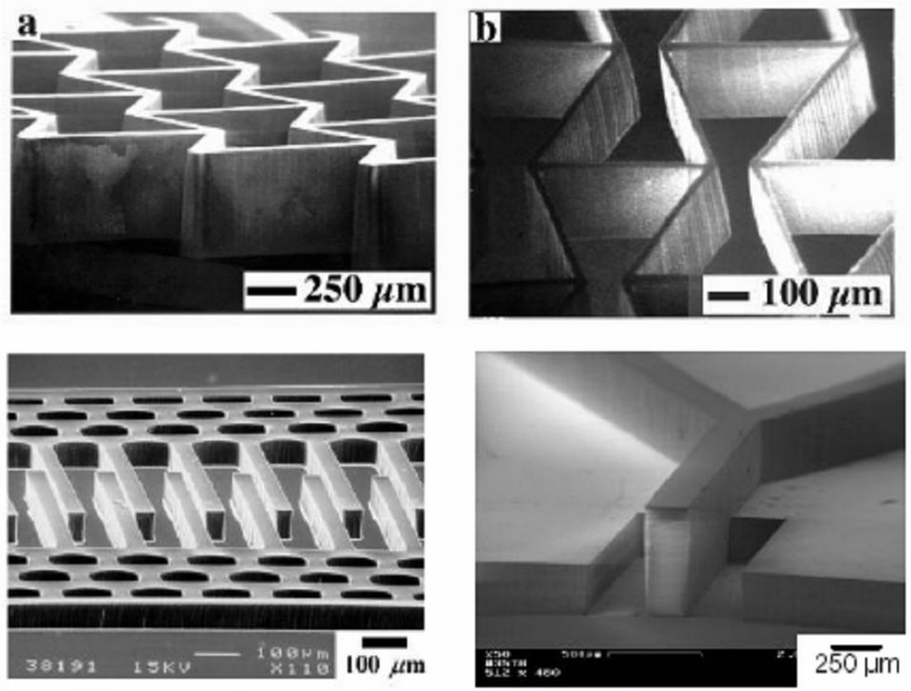
Embossing Microfluidic Systems



SU-8 Resist-Based Microfluidics (1)

SU-8 Resist -- An Alternative to DRIE?

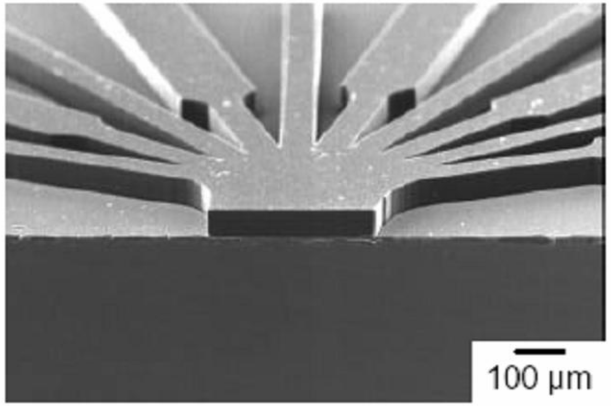
- negative resist
- aspect ratios ~15:1
- thickness > 700 microns
- line width > 25 microns (with R.P.)

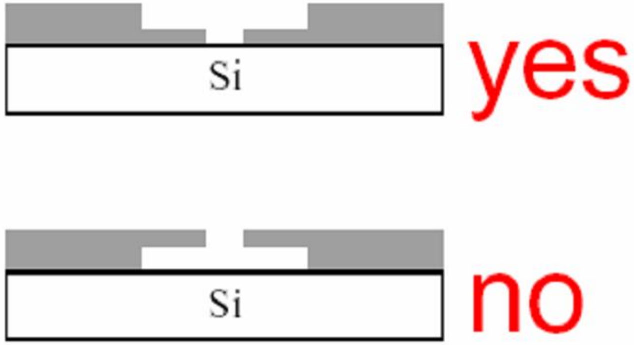


SU-8 Resist-Based Microfluidics (2)

SU-8: An Alternative to Deep Reactive Ion Etching?

- epoxy-based, negative resist developed at IBM
- standard mask aligner used for patterning
- IC-compatible processing conditions



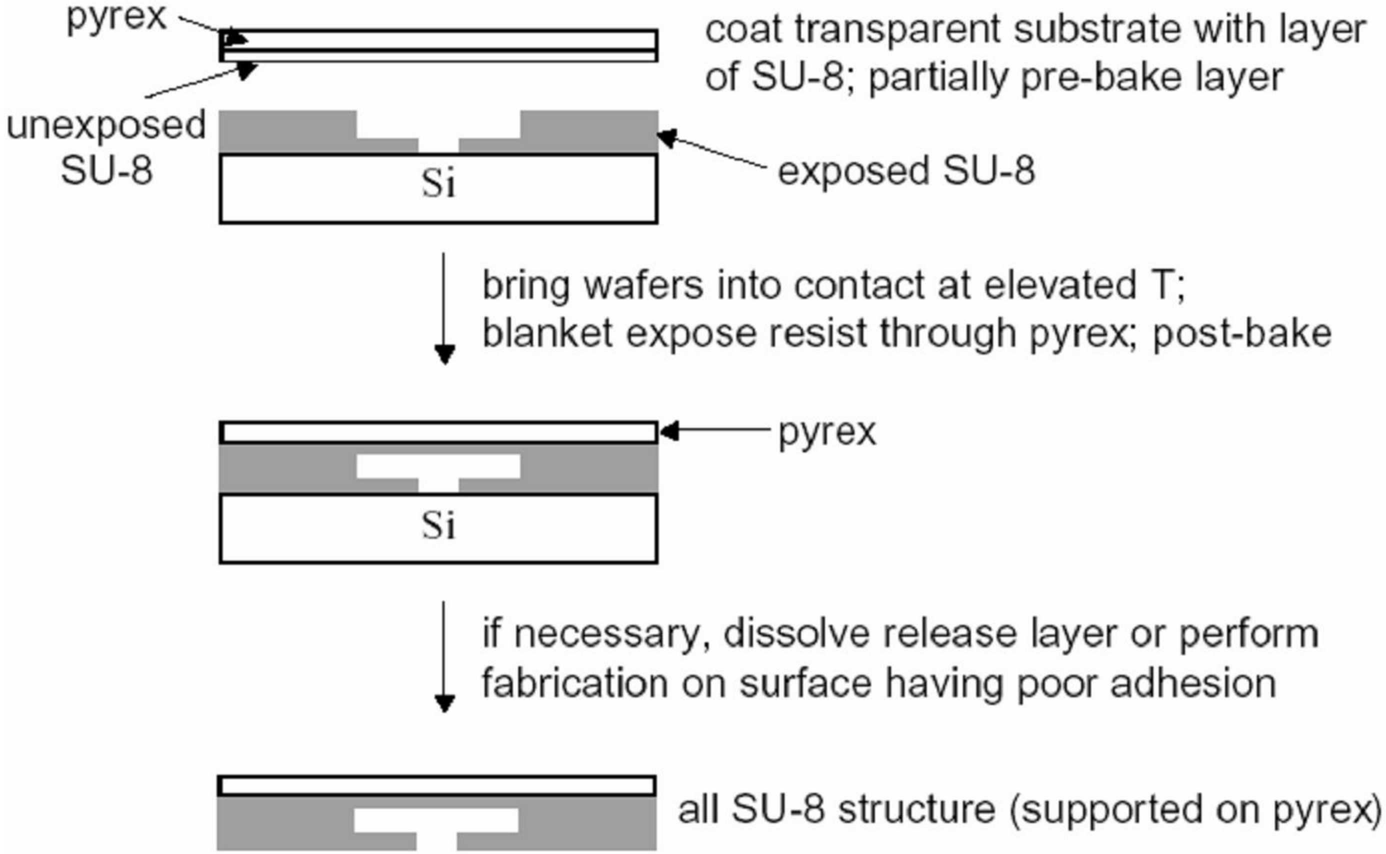


- thick layers are possible -- up to about 700 µm in a single coat
- high-aspect ratio (<15:1) structures can be achieved
- chemically resistant material
- multilayered structures are possible
- contoured surfaces can be planarized

SU-8 Resist-Based Microfluidics (3)

Bonding with SU-8 to form Sealed Microchannels

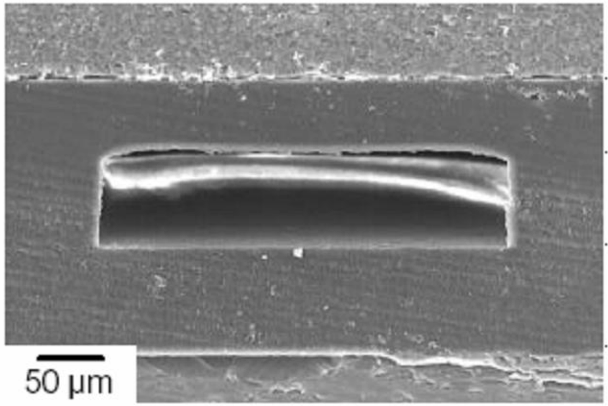
use SU-8 itself as interlayer for bonding full wafers

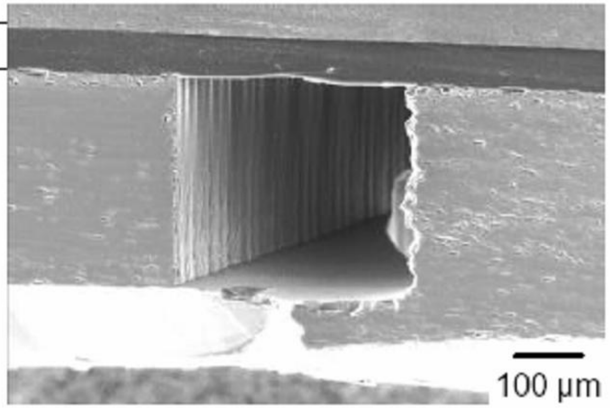


SU-8 Resist-Based Microfluidics (4)

Bonding with SU-8 to form Sealed Microchannels

- maintains dimensions and integrity of multilayered structure
- interface between bonded layers is not apparent



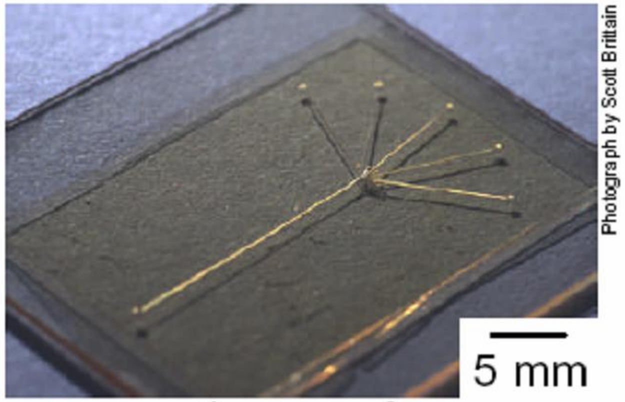


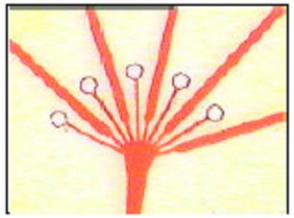
- SU-8 will bond other materials -- requires one uv-transparent layer for exposure step
- exact profile of resulting channel depends on bonding conditions

SU-8 Resist-Based Microfluidics (5)

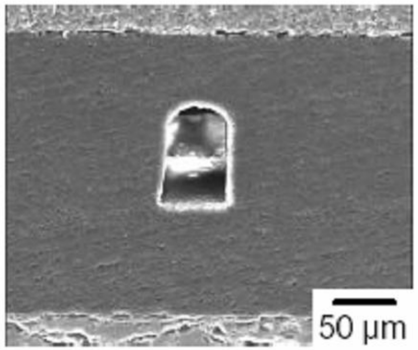
SU-8 Based Microreactors

- produced all SU-8 micromixer with minimum feature size ~ 50 µm
- demonstrated channels are sealed and fluid flow is possible

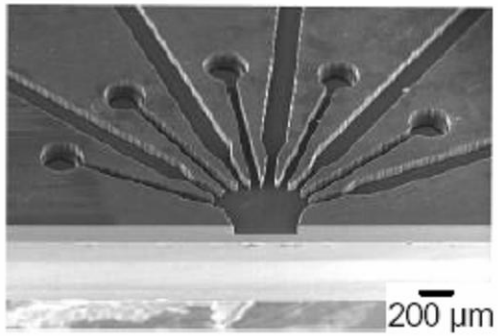




solution of phenol red flowing in channels

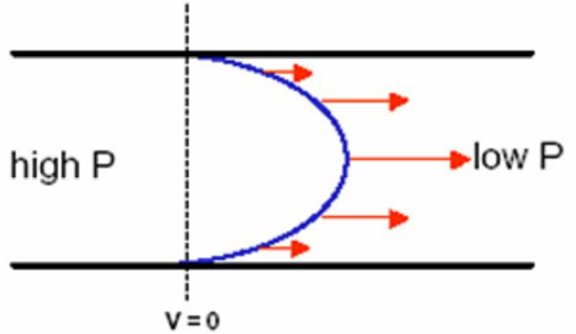


cross-sections through microchannels

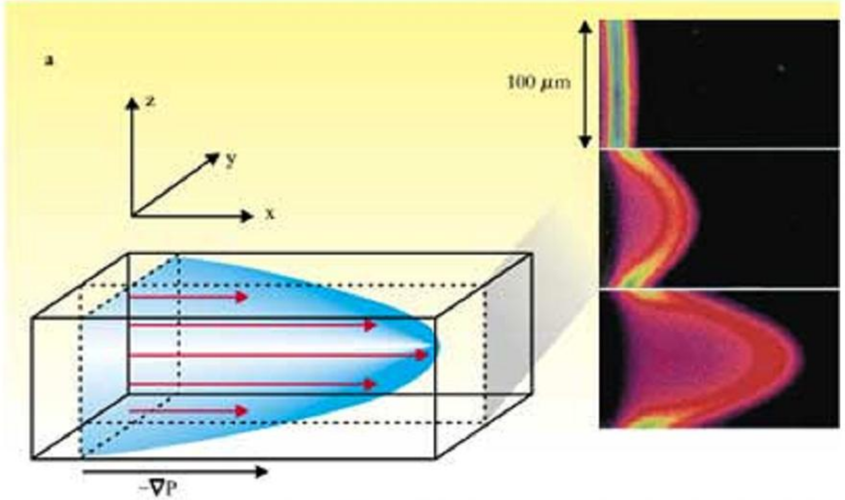


Pumping in Microfluidics

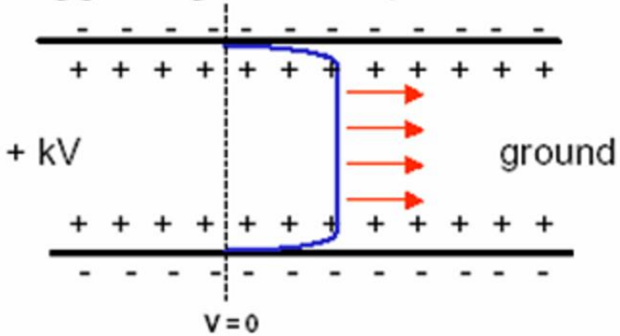
• syringe pump (pressure driven flow)



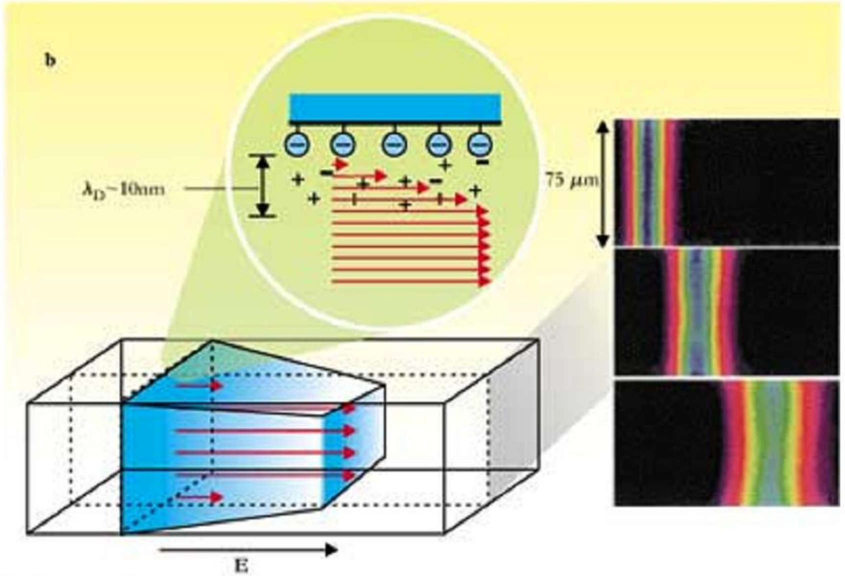
parabolic profile



• applied potential (electro-osmotic flow)



plug flow



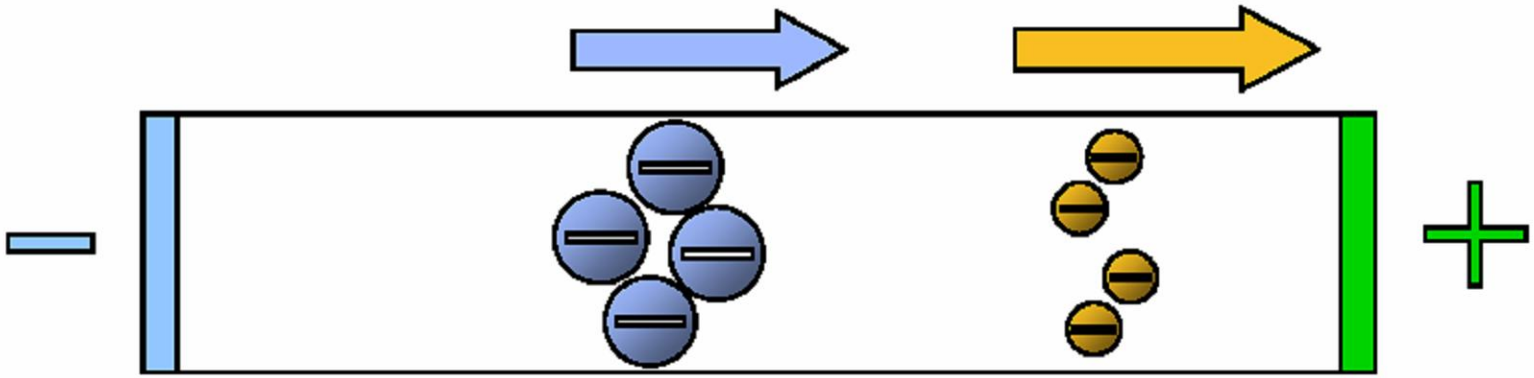
velocity = mobility * electric field

charged particles separated based on mass and charge (electrophoresis)

Electrokinetic Pumping

- Electrophoresis
  - Separation of biochemical species based on electrophoretic mobility (mass-to-charge ratio) under the interaction with an electric field
- Electroosmotic Flow (EOF)
  - Motion of electrolytic solutions near a fixed surface under the interaction with an electric field
- Both electrokinetic mechanisms are critical for a variety of bioseparation technologies, e.g. capillary electrophoresis (CE).

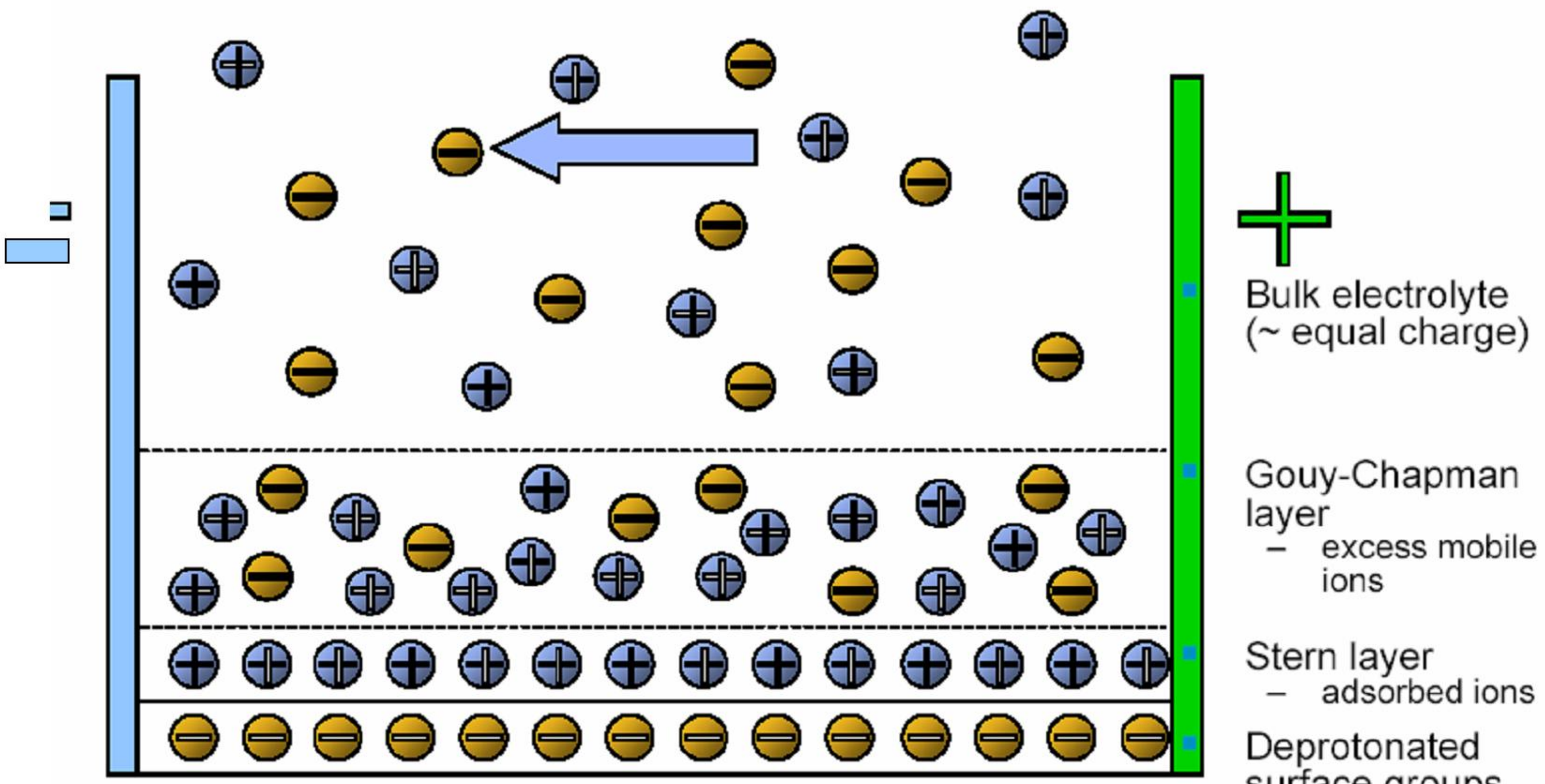
Electrophoresis



Electrophoresis separates charged molecules by size using electric-field-driven transport through a sieve material, typically a polymer gel

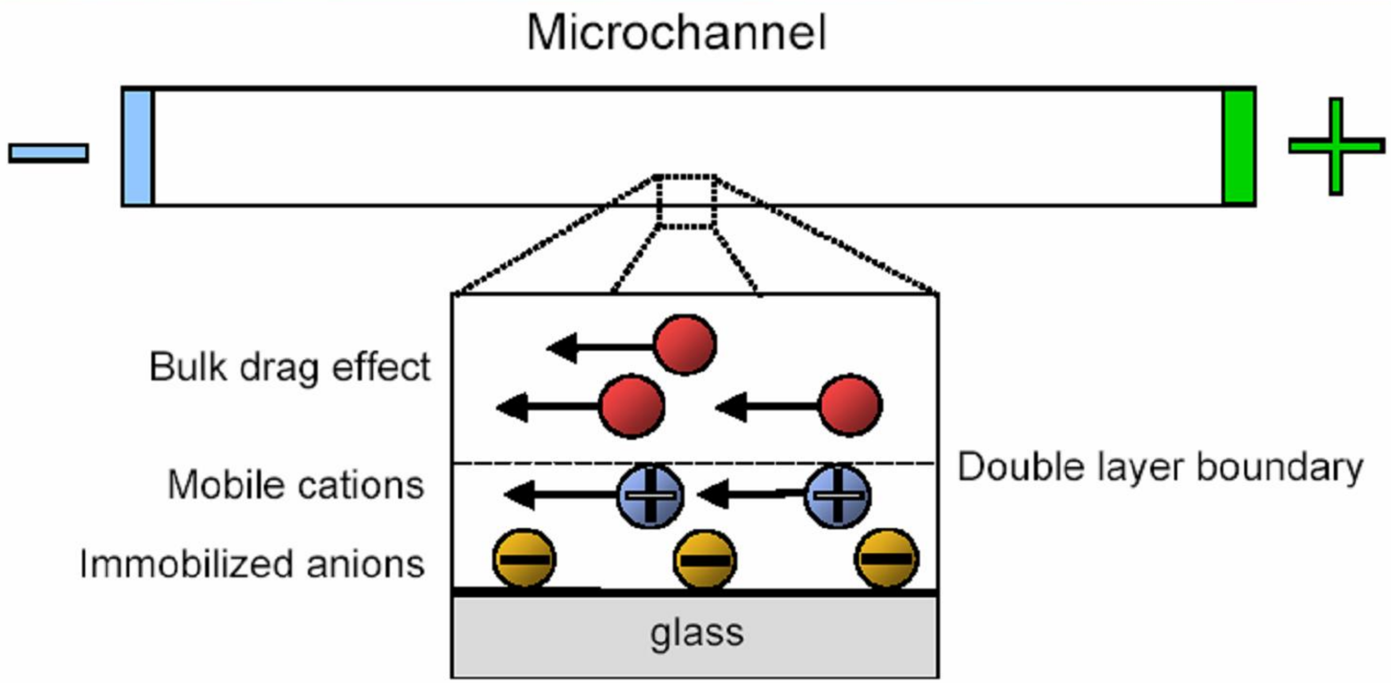
⇒ basis for DNA sequencing

Electro-Osmotic Flow (EOF)



$$u = \frac{-\varepsilon E \zeta}{\mu}$$

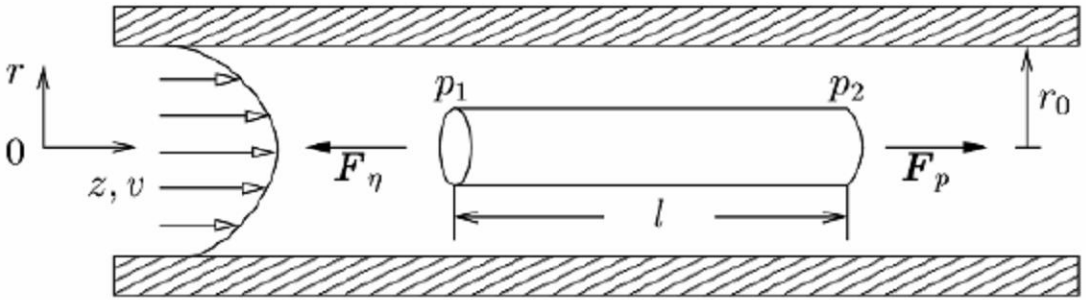
Electro-Osmotic Pumping



- Immobilized charges on the walls of the channels or capillary contribute to formation of double layer of opposite charges.
- The mobile charges move under the influence of the external electric field, causing bulk drag effects (flow rate is linear w/applied potential).
- Packed capillaries can generate 20atm with 2kV. (D = 530um, L = 5.4cm)

Scaling in Microfluidics (1)

Pressure-driven viscous flow in a cylindrical channel: Hagen-Poiseuille flow



- shear forces

$$F_\eta = 2\pi r l \cdot \eta \frac{d\mathbf{u}_z}{dr}$$

- pressure forces

$$F_P = \pi r^2 (p_1 - p_2)$$

$F_\eta = F_P \Rightarrow$

Equating shear and pressure forces

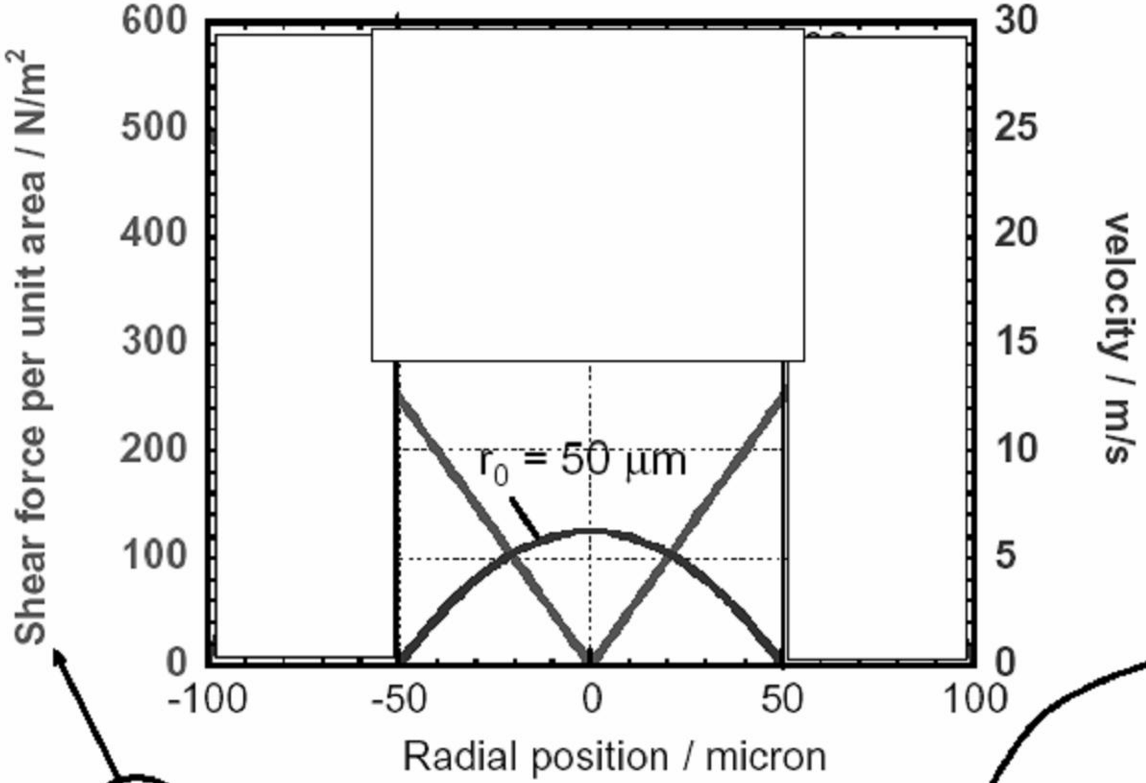
$$\frac{d\mathbf{u}_z}{dr} = \frac{r\Delta \mathbf{P}}{2\eta l}$$

$$\mathbf{u}_z(r) = \frac{\Delta \mathbf{P}}{4\eta l}\left(r_0^{\ 2} - r^2\right)$$

Ducree and Zengerle, IMTEK

Scaling in Microfluidics (2)

Cylindrical capillaries, r_0 = 100 and 50 μm, pressure drop 100 atm/m

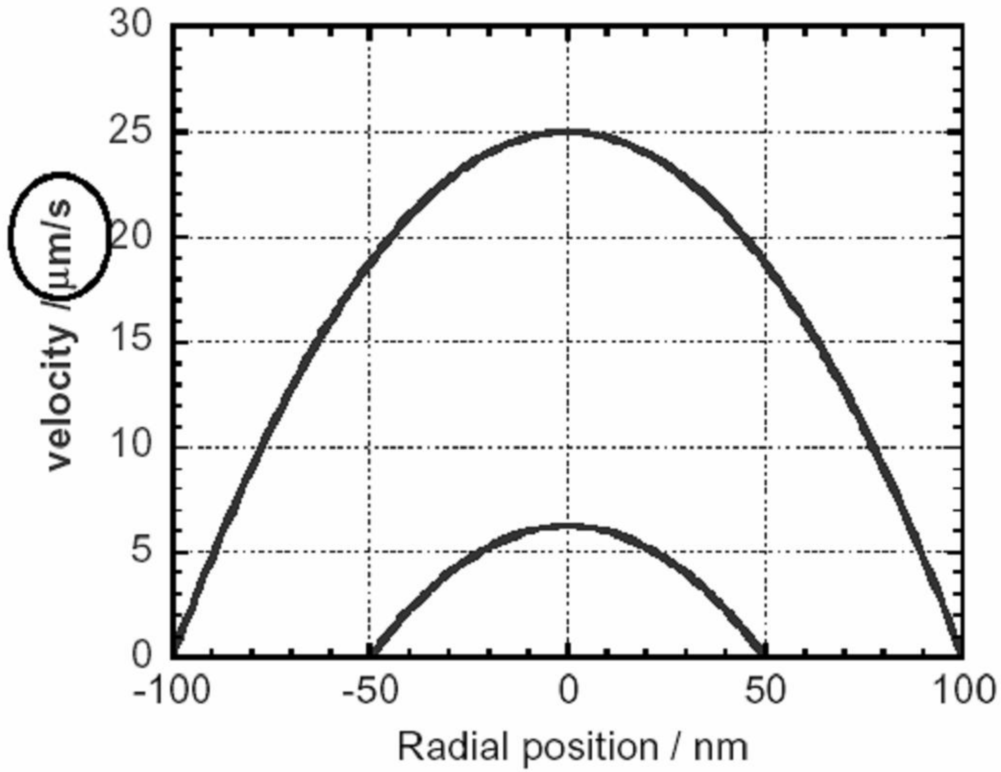


$$\frac{d\mathbf{u}_z}{dr} = \frac{r\Delta\mathbf{P}}{2l}\frac{1}{\eta}$$

$$\mathbf{u}_z(r) = \frac{\Delta\mathbf{P}}{4\eta l}\left(r_0^{\,2} - r^2\right)$$

Scaling in Microfluidics (3)

Cylindrical capillaries, r_0 = 100 and 50 nm, pressure drop 100 atm/m



- velocity scales with r_0^2
- volume flow rate (velocity*area) scales with r_0^4

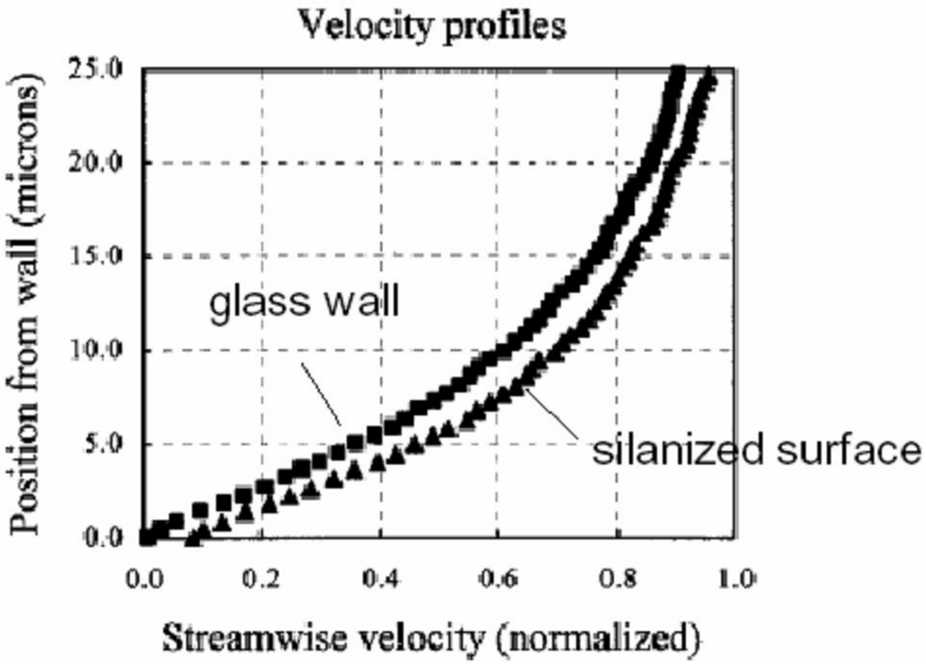
Scaling in Microfluidics (4)

Scaling pressure-driven flow

- Pressure force ($\propto 1/r^2$) decreases faster than shear (friction) force ($\propto 1/r$)
- Velocity scales with $1/r^2$ and volume flow rate with $1/r^4$
- Need for high pressures to get 'reasonable' flow rates in nanochannels
- Two other possible ways out: using slip flow or electroosmotic flow

Scaling in Microfluidics (5)

Slip flow: decrease wall friction

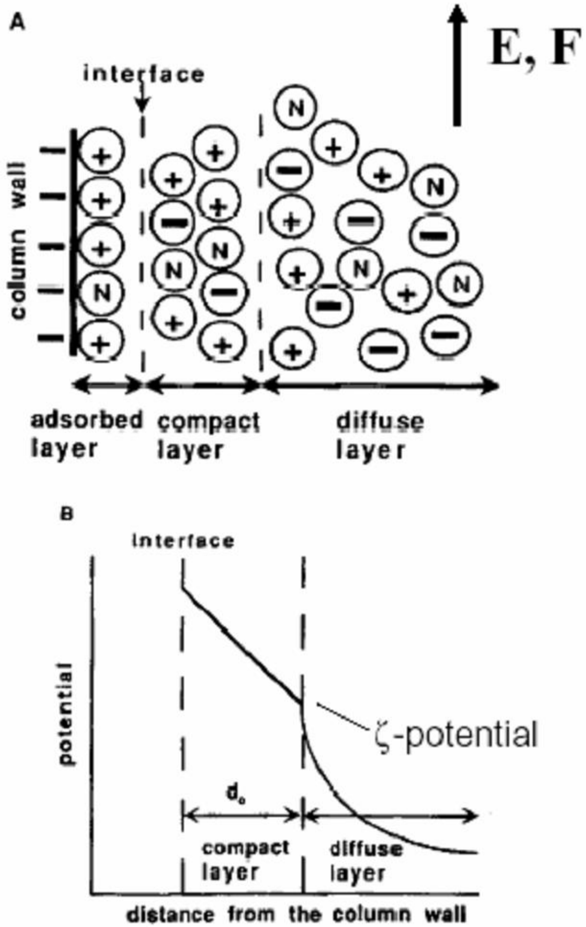


Solvent/wall interaction can be decreased by functionalizing the wall;
Wall boundary condition becomes 'slip' instead of 'non-slip'.

Tretheway, Meinhart, Phys. Fluids, 14 (2002) L9

Scaling in Microfluidics (6)

Electroosmotic flow



Exert a Coulomb force on the excess mobile charge in the diffuse double layer

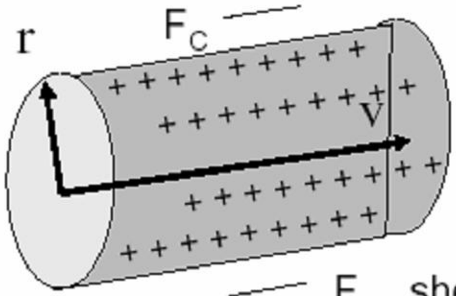
Order-of magnitude approximation for the Coulomb force per unit area:

$$\frac{\mathbf{F}_C}{A} = \rho \lambda_D \mathbf{E}$$

Coulomb force per unit area =
(space charge density ρ)*
(Debye screening length λ_D)*
(electric field **E**)

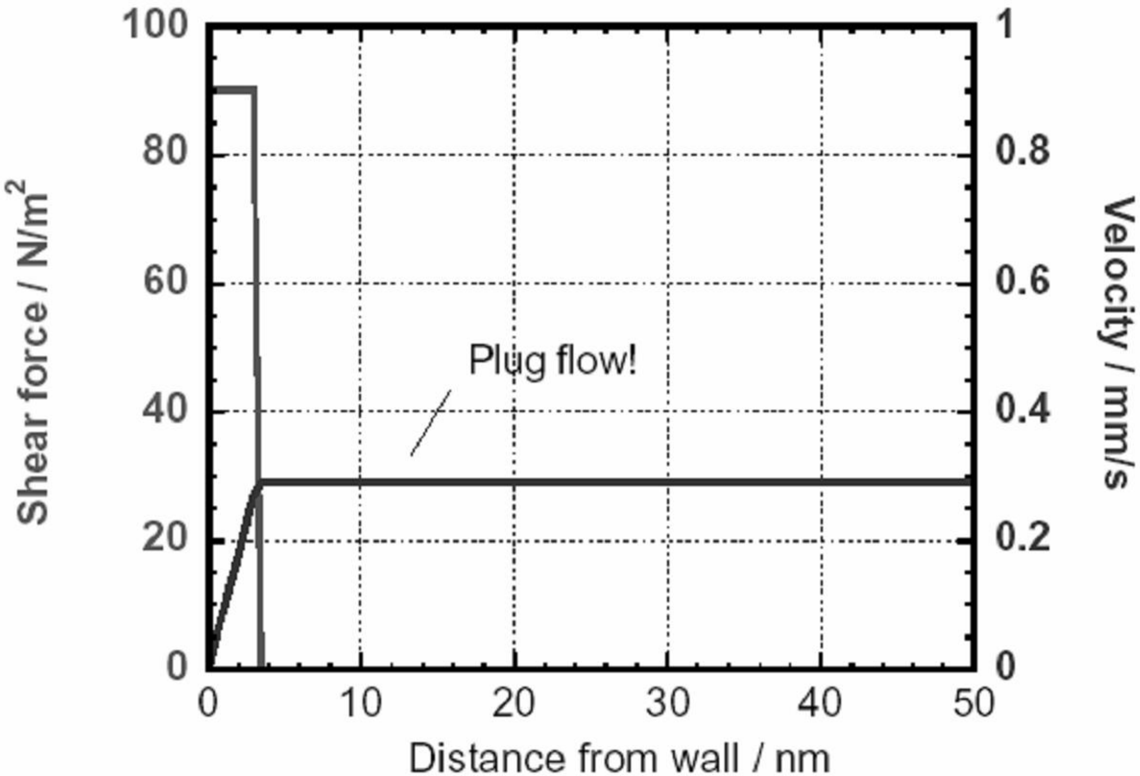
Scaling in Microfluidics (7)

Electroosmotic flow scaling



Velocity independent of channel radius!

Scaling in Microfluidics (8)



$$\mathbf{u}_{\text{eof}} = \frac{1}{\eta}\int_0^{\lambda_D} \rho \lambda_D \mathbf{E} dr = \frac{\rho {\lambda_D}^2 \mathbf{E}}{\eta}$$

Example: space charge density in diffuse layer $\rho = 10^6$ C/m^3; ionic strength = 10 mM; λ_D = 3 nm; **E** = 30,000 V/m

Scaling in Microfluidics (9)

Conclusion electroosmotic flow

- Both force and friction scale with 1/r
- Velocity independent of r!
- Plug flow
- But what if the radius is smaller than the Debye length (double layer overlap)?

  (at low salt concentrations or small radii)