國立臺灣大學 National Taiwan University

543 U6960

Lab On a Chip:

Microfluidics (II): Microchannel Fabrication

April 16th, 2013

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Ink Jet Printing / Droplet Generator

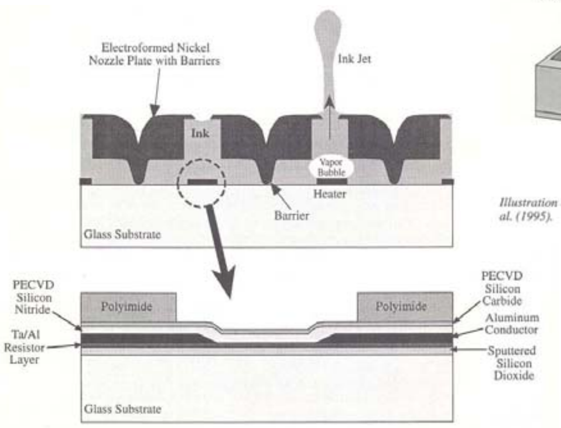


Illustration of Hewlett-Packard ink-jet devices, showing bonded electroformed nickel nozzle plate and multi-layer thin-film heaters. After Allen, et al. (1985) and Bhaskar and Aden (1985).

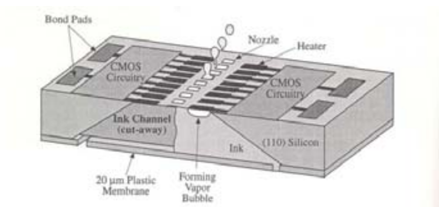
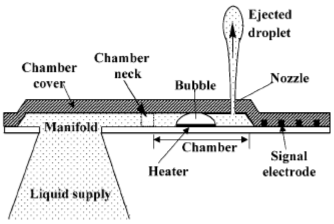
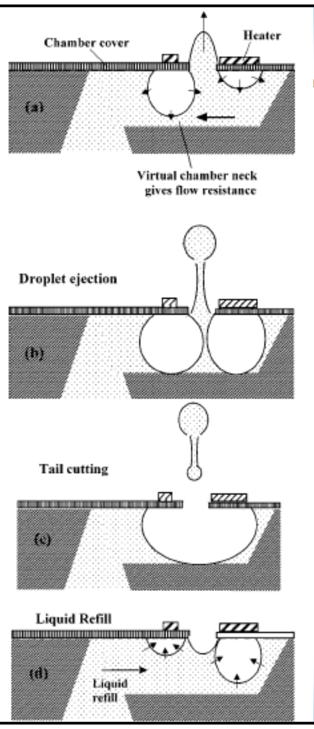


Illustration of a fully integrated CMOS ink-jet print head design. After Krause, et al. (1995).



Tseng, Kim, Ho



Applications of microchannels

Cooling Microelectronic Devices

Microchannel heat sink; micro heat exchanger.

Micro Actuators

Micropump; dosing system.

Micro Sensors

Thermal flow sensor; pressure sensor; densiometer.

Passive Components

Micro valves; micro filters.

Power MEMS

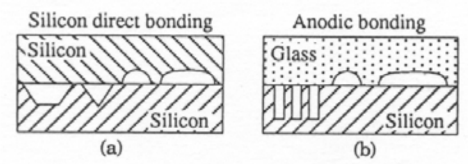
Micro combusters; micro fuel cells.

LOC (Lab-On-A-Chip); Micro Total Analysis System (μ-TAS)

Gas or liquid chromatography; electrophoresis; drug delivery.

Microchannels before MEMS Era

- Isotropically etched grooves (Terry 1979)
- Crystal-orientation-dependent etching (Tuckerman 1981)
- Other possible methods
  - Mechanical precision sawing
  - Electric discharge machining
  - Numerical controlled machining
  - Reactive ion etching
  - Laser machining
  - Electro-chemical machining
  - Ion milling
  - Hot embossing
- Limitations on
  - Channel geometry
  - Process temperature
  - Integration
  - Interconnection



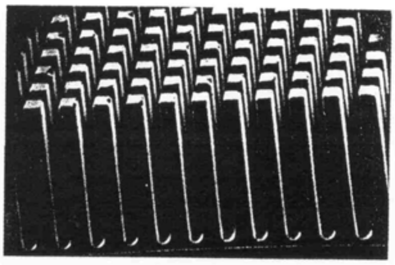
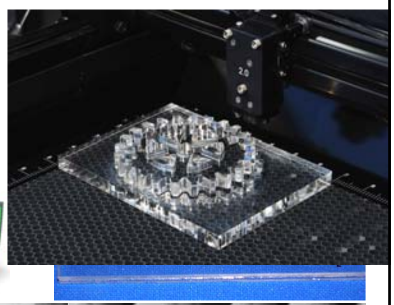
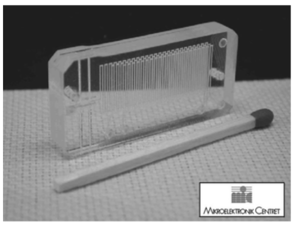
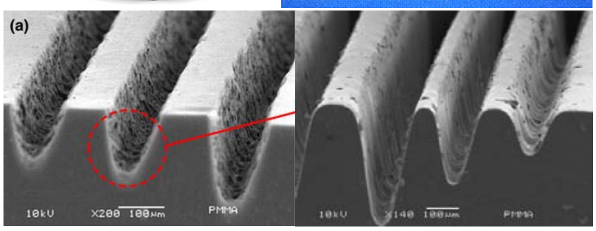


Figure 3.3: SEM of rectangular pin-fin structures fabricated in silicon by precision mechanical sawing. The spatial period is 80 μm in both directions [Tuckerman (1984)].

Laser Machining







SEM image of PMMA substrate with channels of different depths produced by unfocused laser beam @ W and scanning © 屏科大

- So…..how you want channels made at microscale?
- Minichannel? Microchannel? Nanochannel?

Microchannels

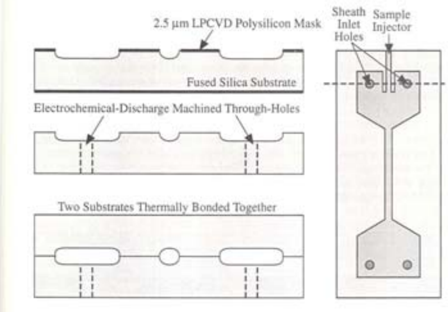
- Microchannel Fabrication
- Microchannel Functions:
  - Transportation
  - Mixing
  - Separation
- Pumps
- Active Mixing vs Passive Mixing
  - see previous lecture by Prof. 楊鏡堂 @ NTU, ME, a leading expert in the field.
  - Hydrodynamic focusing
  - Why and how chaotic mixing?
- T-sensor (Y, H…etc)

- Fabrication

Microchannels

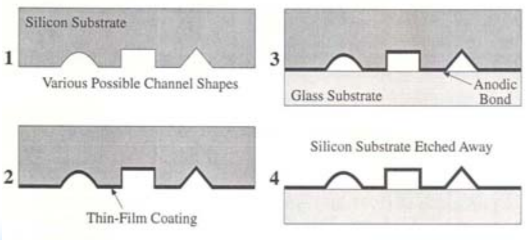
- Types of Fabrication Processes
  - Bulk micromachining (Si, glass, quartz,..)
  - Surface micromachining (Solid materials, polymers)
  - Others (Thick-PR lithography, Micromolding, Imprinting, replication,..)
- General Considerations
  - Channel cross-sectional areas and other geometric constraints
  - Channel interior surface materials (whether or not all surfaces are of one material type, and if the materials(s) is (are) biocompatable
  - Complexity of fabrication (yield and cost)
  - Flexibility in tubing and in integration with other fluidic components
  - Optically accessible (Transparency, thickness of bonding glass,.)
  - Hermeticity, surface roughness

Bulk Micromachined Channels

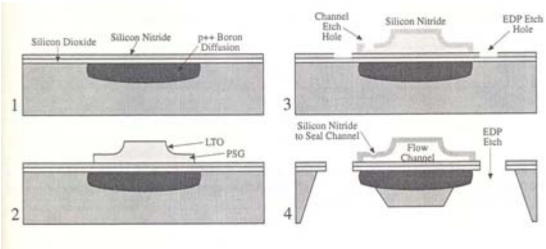


Micromachined flow cytometry cell (Sobek)

Thin fluidic channels (Tjerkstra)



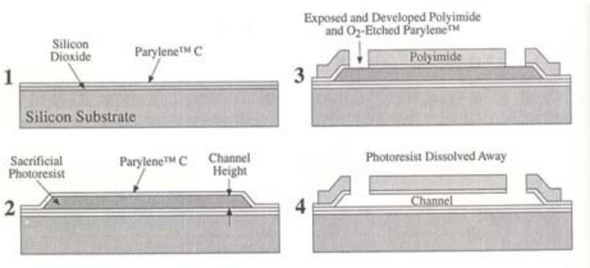
Surface Micromachined Channels



Need-like neural probe (Lin)

Surface micromachined organic fluidic channel (Man)

- Low temperature process



Geometry control

MALLIK *et al.*: FABRICATION OF VAPOR-DEPOSITED MICRO HEAT PIPE ARRAYS

Triangular cross-section microchannel made by vapor deposition

(Mallik et al. 1995)

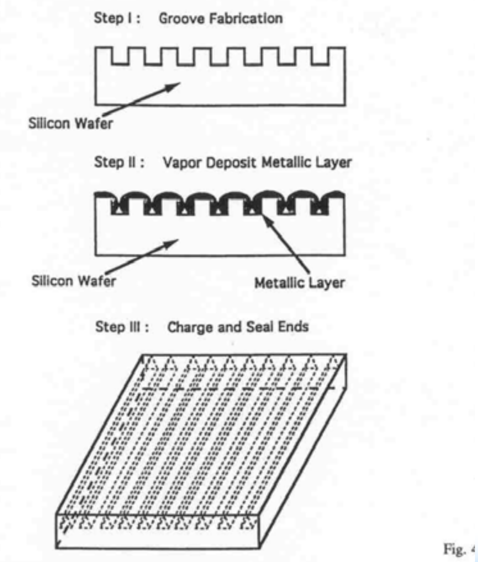


Fig. 3. Fabrication of vapor-deposited micro heat pipe array.

Geometry control

Hexagonal cross-section microchannel made by anisotropic etching and wafer bonding (Enoksson et al. 1996)

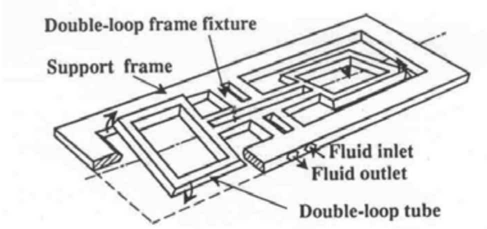


Fig. 2. The resonant planar tube system oscillating in a balanced torsic mode.

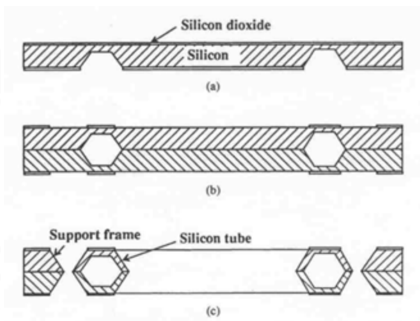
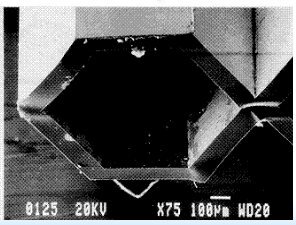


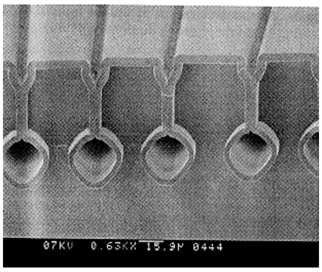
Fig. 4. Cross-sectional view of the schematic fabrication sequence based on micromachining and fusion bonding of single-crystalline silicon.

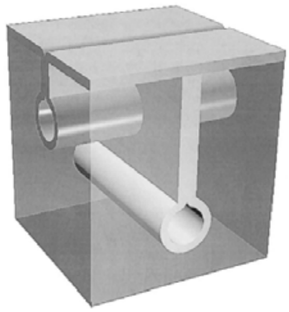


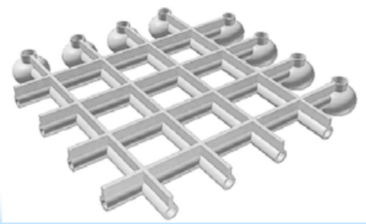
Free standing hollow tubes for liquid density sensing.

Geometry control

Circular buried micro channels (BCT) by wet anisotropic, wet isotropic, dry anisotropic, and dry isotropic silicon etching followed by LPCVD sealing or glass wafer bonding (Tjerkstra 1997, Boer 2000)

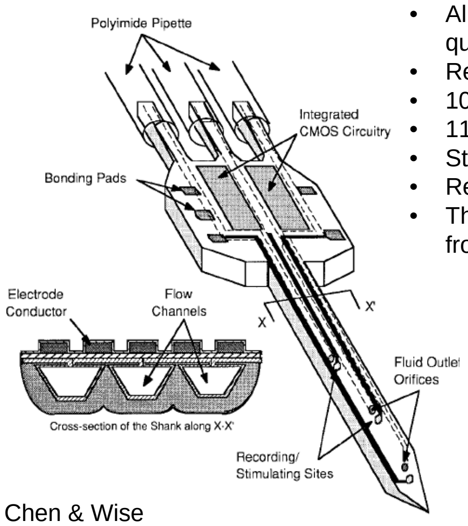






Can form channel networks or multi-lever channels

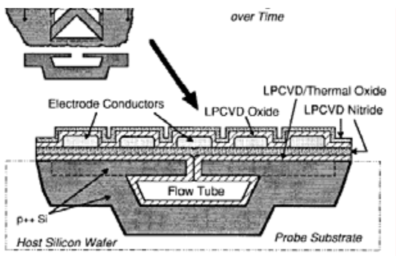
Microchannel for neural probes



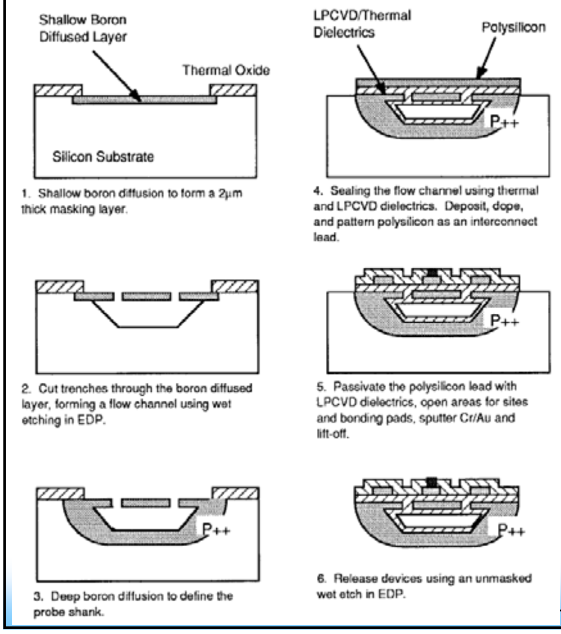
Chen & Wise

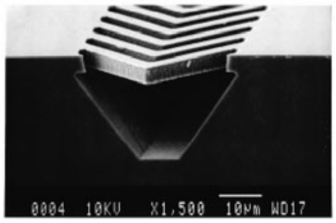
Fig. 3. Perspective view of a micromachined drug-delivery probe havin three delivery channels along with recording and stimulating electrodes.

- Allowed the controlled injection of minute quantity (100 pl)
- Recording of neural signals
- 10 μm wide, 4 cm long
- 11 torrr drive pressure, 1.3 mm/s
- Stimulate neurons by delivering chemical
- Record the electrical signal as response
- The structural of the probe is fabricated from p++ silicon

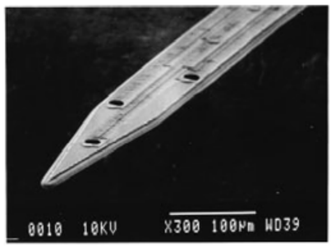


Microchannel for neural probes





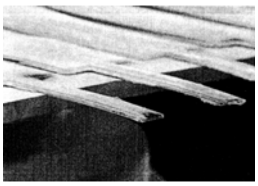
after step 3



the final device

Metallic microchannels

Surface micromachined metallic microchannels
(Papautsky et al. MEMS '97)



SEM of an array of metallic μchannels

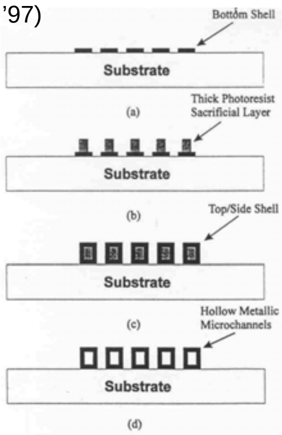


Figure 3. Microchannel fabrication procedure. (a) electroplate bottom shell; (b) apply and pattern thick photoresist; (c) deposit metal forming side walls and top shell; (d) remove thick photoresist using acetone bath.

Formation of a dense array

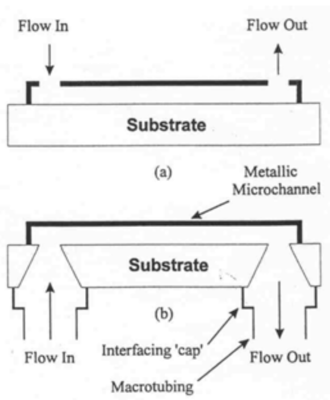


Figure 4. Microchannel interface scheme. (a) access ports in the top wall of a microchannel; (b) back side access ports by etching through the substrate.

Two configurations of fluidic interconnection

SU-8 microchannels

Guerin et al., Transducer '97

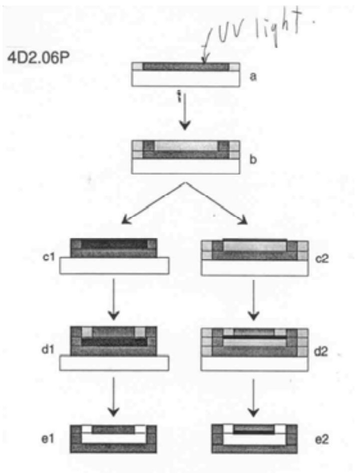
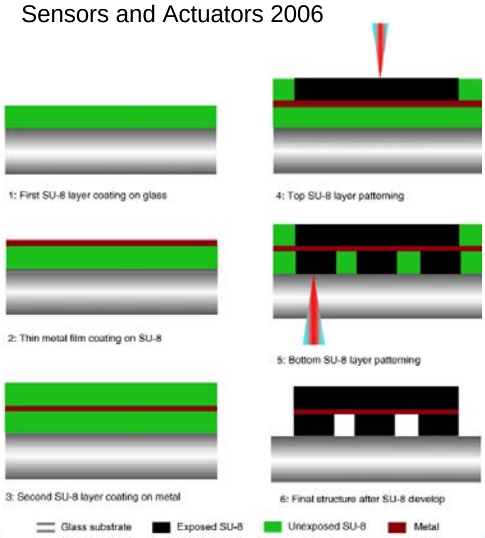


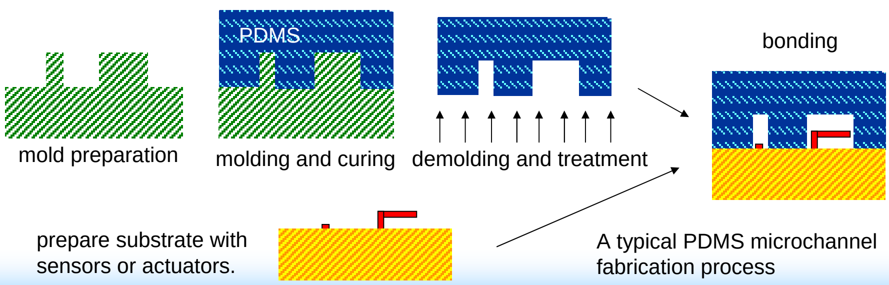
Figure 1: Fill- and mask-process-flow for micro-channel fabrication. Light grey: nonpolymerized SU-8; middle grey: polymerised SU-8; dark grey: filling material; black: metal.

Yu, Li and Zhang,
Sensors and Actuators 2006



PDMS microchannels

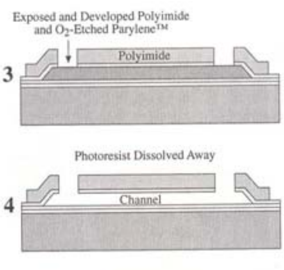
- Very popular for BioMEMS
  - Low cost
  - Rapid fabrication
  - Superior material property:
    Biocompatible, hydrophobic, transparent, flexible, gas permeable…
  - Geometry control by micromachining of mold (Si, PR…)
  - Easy bonding at low temperature (after O_2 plasma treatment):
    reversible: PDMS - glass, silicon etc. or irreversible: PDMS – PDMS

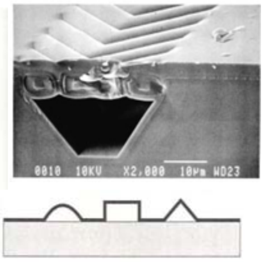


A typical PDMS microchannel
fabrication process

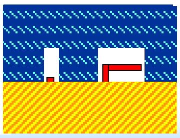
Key elements of MEMS microchannel fabrication techniques

- Selective etching of sacrificial material to form channel
- Micromachining control of channel geometry
- Deposition sealing of releasing holes
- Bonding as another option for enclosure
- Micromolding to boost the material process ability and decrease the cost.





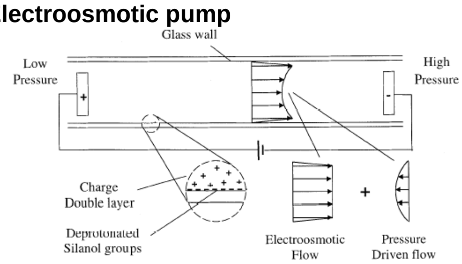
bonding

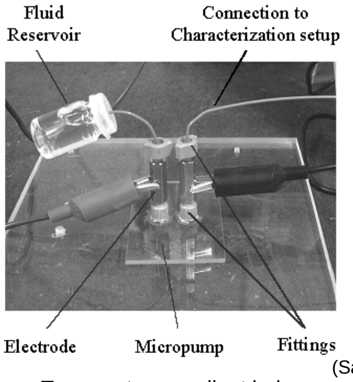


- Microfluidic Transportation in Microchannels
  - 驅動：Pump (embeded vs outside)
  - 開關：Valve

Example: Micropumps

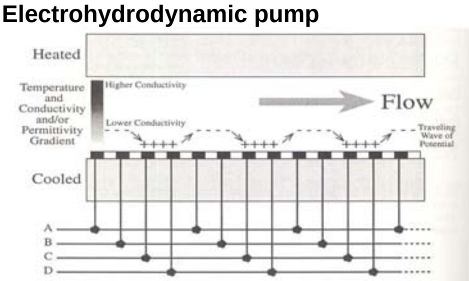
Electroosmotic pump





(Santiago)

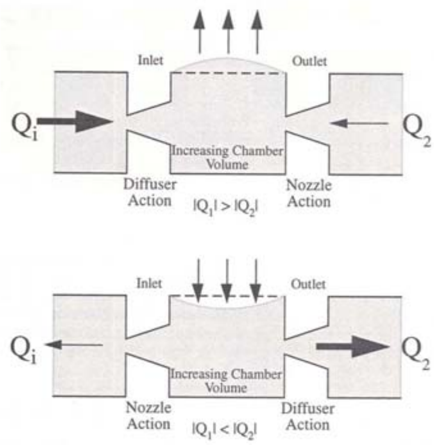
Electrohydrodynamic pump



(B. Wanger)

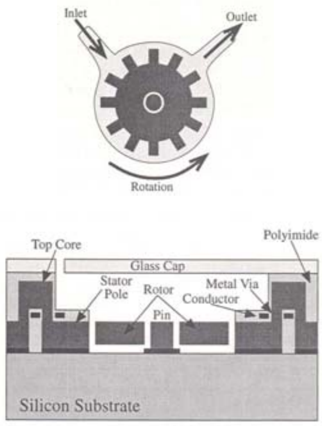
- Temperature gradient induces conductivity and permittivity gradients
- Traveling wave of electric field induces charges on the interface and in the bulk flow
- The traveling filed also drive the induced charge, and thus the flow

Diffuser and Rotary Pumps



Diffuser pump (Stemme)

- More fluids in the Diffuser direction than in the Nozzle direction, resulting a new flow



A rotary "jet type" magnetically driven pump (Ahn and Allen)

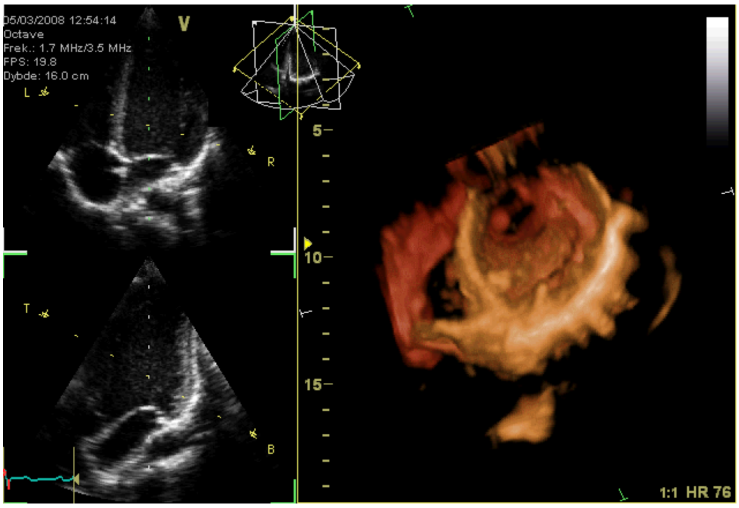
- 24 ul/min at 5000 rpm
- Differential pressure 0.1 atm

Microvalves

- Ideal valves should have the following characteristics :
  - Zero leakage
  - Zero power consumption
  - Zero dead volume
  - Infinite differential pressure capability
  - Insensitivity to particulate contamination
  - Zero response time
  - Ability to operate with liquids and gases of any density/viscosity/chemistry

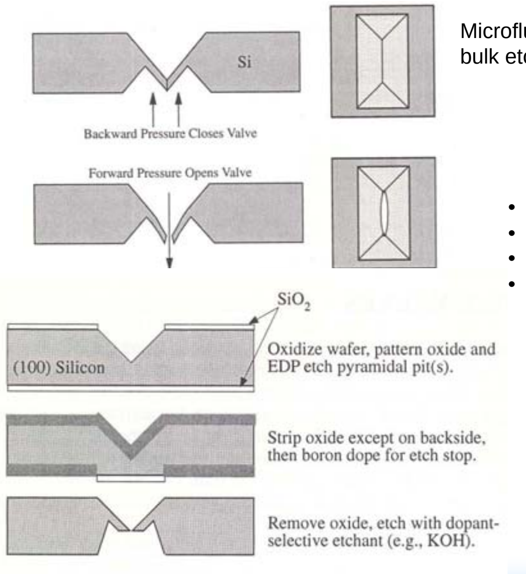
  Why this is a challenging ?
- Mechanisms
  - Passive (no power required)
  - Active (require a powered actuation mechanism)

Heart Valve



Bicuspid/Mitral valve, Tricuspid valve
Aortic valve, Pulmonic valve

Passive Valves

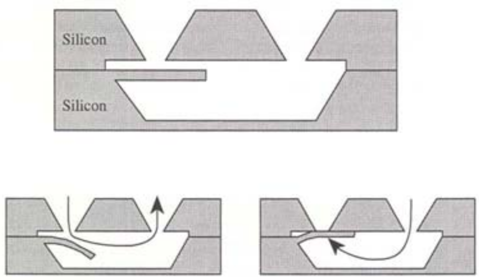


Microfluidic valve fabricated using two-sided bulk etching (Smith and Hok)

- KOH to form pryamidal pits
- Slit widths ~ 10 μm
- Thickness of leaflets
- Leakage problem

Control ?

Passive Valves



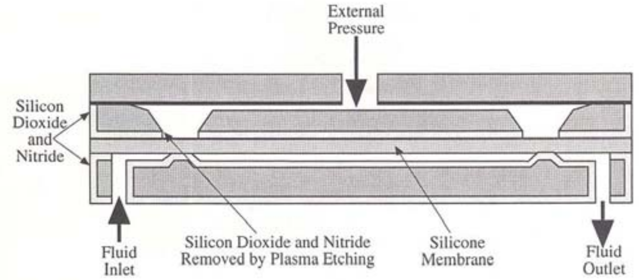
A two-wafer stack, bulk micromachined passive valve (Tiren)

- A single cantilever acts as a seal when forced against the upper wafer by reverse flow
- In addition to the bulk micromachined valve design combined with a fuel injection nozzle

Active Valves

- Actuation Mechanisms
  - **Thermal actuation** (linear thermal expansion, thermal bimorph, shape memory alloys):
    + generate large forces,
    + good when scaling down devices (thermal mass decreases)
    - relative slow (especially with passive cooling),
    - undersirably heat the sample fluid,
    - consume a lot of power
  - **Piezoelectric actuation**
    + yield very high forces
    - small movement even with large voltage
  - **Electrostatic actuation**
    + high forces, large movements
    - non-linear force
  - **Pneumatic and Thermopneumatic actuation**
    + high forces and movement
    - power consumption, undesirable heating in samples

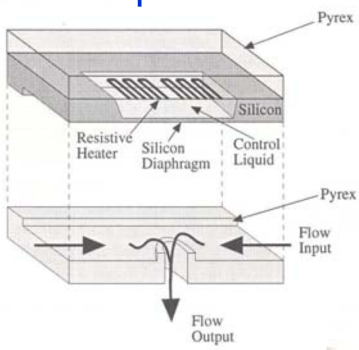
Pneumatic Valves



A silicone elastomer membrane, micromachined pneumatically actuated microvalve. (Vieider)

- The design consists of three wafers in a stack, the central one containing the moving plunger and silicone membrane
- Pressure difference up to 500 kPa
- Require an external pump, adding complexity in on-chip integration

Thermopneumatic Valves

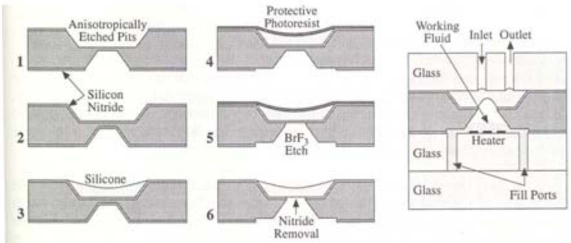


Micromachined thermal expansion valve (Zdeblick)

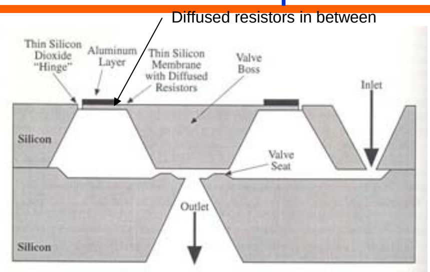
- Membrane thickness ~ 50 μm
- Sealed with anodic bonding (high sealing quality is required)
- Power required 1-2 W
- Silicon membrane do not have high flexibility => smaller deflection, higher leakage

Micromachined, silicone membrane, thermopneumatic valve (Yang)

- Membrane thickness ~ 50 μm
- Peak membrane deflection 860 μm at 970 mW
- 20 psi at 280 mW with air flow rate 1.3 lpm



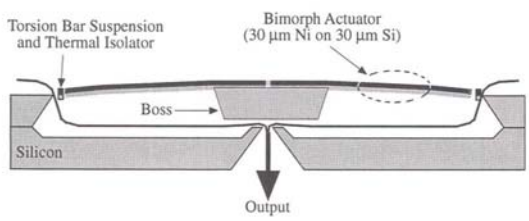
Thermal Bimorph Valves



Thermal bimorph valve (Jerman)

- A thin SiO2 "hinge" surrounding the membrane to increase thermal isolation and provides a hinged boundary for the membrane
- Inlet pressure 1- 50 psi with an input power of 150 mW

Thermal bimorph valve (Barth)

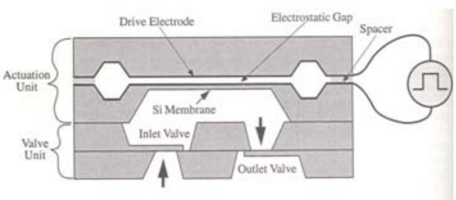


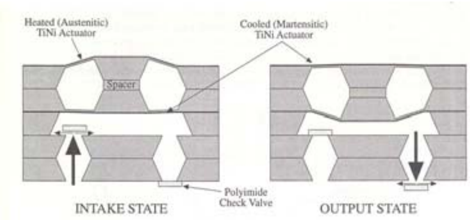
Micropump + Valves

- Mechanisms

Share the same actuation mechanism in the design of active microvalves

- Thermal actuation
- Piezoelectric actuation
- Electrostatic actuation
- Pneumatic and Thermopneumatic actuation





Electrostatic pump (Zengerle)

- Incorporate two check valves
- Frequency range: 0.1 Hz to > 10 Hz
- Flow rate : 250-850 μl/min

Thermal Expansion pump (Benard)

- Flow rate 50 ul/min at 0.9 Hz with 0.6 V, 0.9A (0.54W)

- Mixing

Micro Mixers

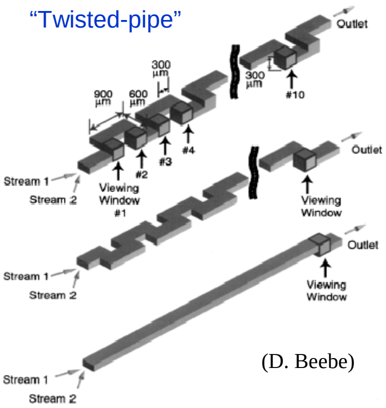
- Rapid mixing can substantially save the time in a bioanalytical system
- At Low Reynolds number region, there is no turbulence for enhancing mixing
- Effective mixing requires that fluids be manipulated to increase the interfacial surface area

- Passive mixers
  they utilize no energy input except the mechanism used to drive the fluid flow at a constant rate

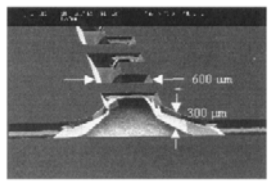
- Active mixers
  they exert some form of active control over the flow field through such means as moving parts or varying pressure gradient

Passive Mixing in a 3-D Serpentine Microchannel

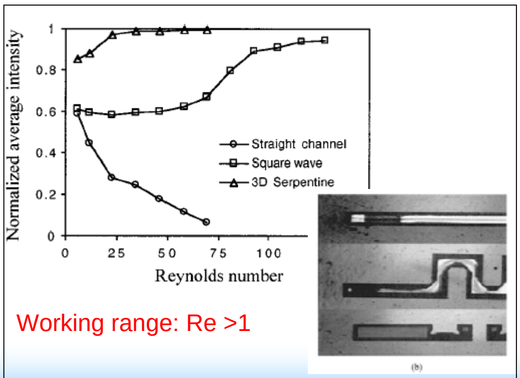
"Twisted-pipe"



(D. Beebe)

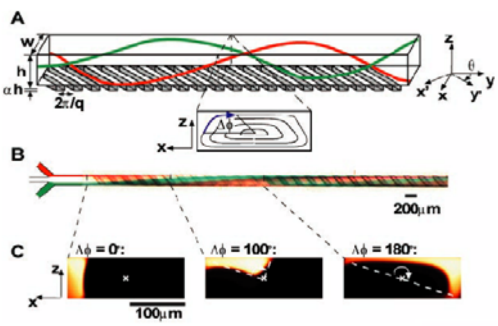


- Chaotic advection: simple regular velocity fields produce chaotic particle trajectories. This typically indicates rapid distortion and elongation of material interfaces. This process significantly increases in the area across which diffusion occurs.
- The flow change in direction result in flow separation caused by momentum of the fluid, leading to folding of the flow



Working range: Re >1

Passive Chaotic Mixer

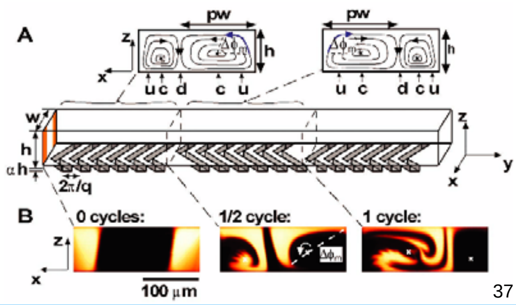


- 3-D twisting flow with obliquely oriented ridges on on wall
- The ridges cause an anisotropic resistance to the flow: less resistance in the direction parallel to the ridge
- A pressure gradient in the transverse direction is therefore generated
- The fluid circulates back across the top of the channel

$$\mu \nabla^2 U = \nabla P$$

(Stroock & Whitesides)

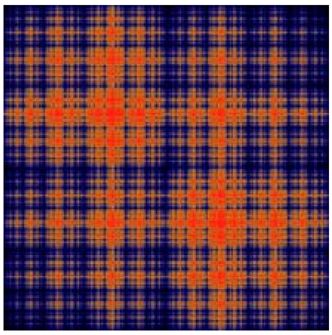
Working range : 100> Re >0



Staggered herringbone mixer

Making bread (metaphor of chaos)

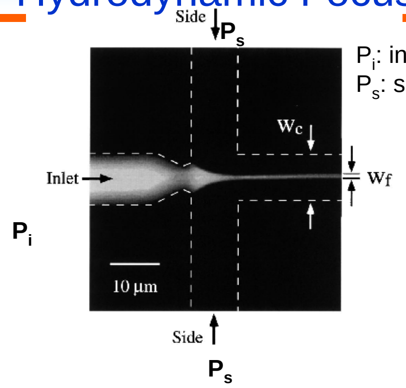
gliadin + glutenin proteins
→ strands of gluten (麥麩)

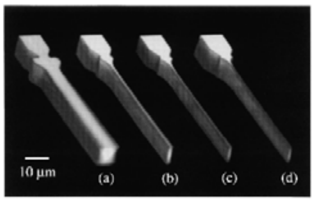


baker map:
a chaotic map from the unit square into itself

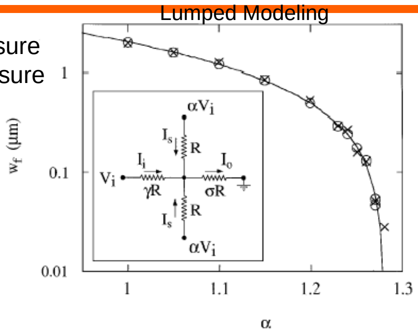
Hydrodynamic Focusing Micro Mixer

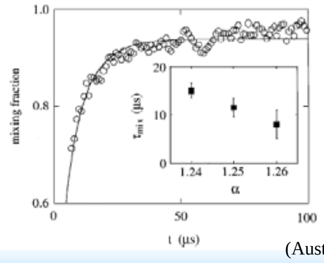
P_i: inlet pressure
P_s: side pressure





Lumped Modeling

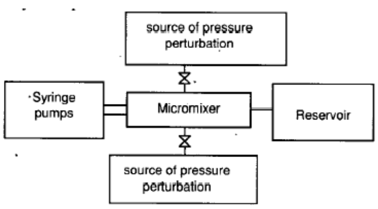




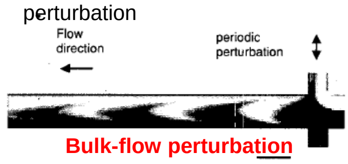
(Austin)

Active Chaotic Mixers

- Pressure-Driven Actuation



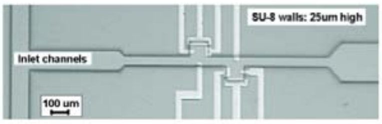
- Inducing flow folding and stretching by adding unsteady hydrodynamic pressure perturbation

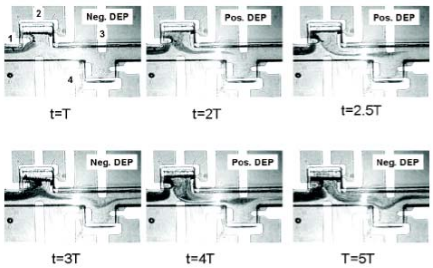


Bulk-flow perturbation

100 um (Lee & Ho)

- DEP-Driven Actuation





Lyapunov exponent: to characterize the rate at which pairs of fluid particles diverge and characterize the degree chaotic effect

$$\lambda_\infty = \lim_{t\to\infty} \frac{1}{t} \ln \|(T_{\mathbf{x}}\mathbf{v})\hat{\mathbf{w}}_0\|$$

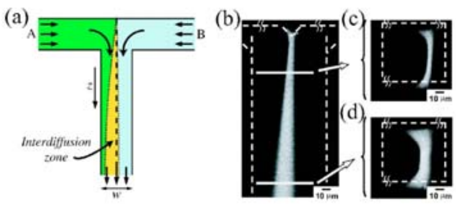
$\lambda > 0.4$

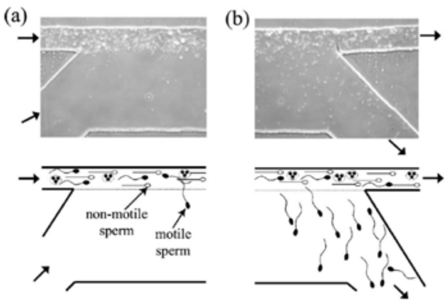
Particles perturbation (Deval & Ho)

- Separation

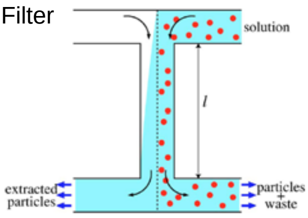
Microscale Laminar Flows

T Sensor





H Filter

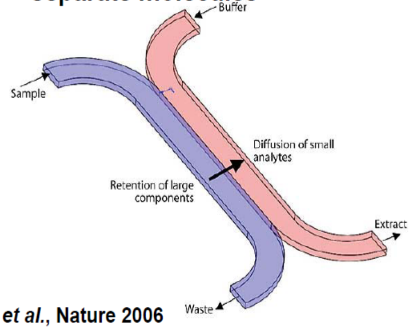


A variant of the H filter that separates motile from nonmotile sperm. While the traditional H filter relies upon particle diffusivity differences for differentiation, this device exploits the fact that motile sperm disperse across and homogenize the channel much more rapidly than nonmotile ones, which spread via diffusion alone. (Cho, Schuster, *et al., ACS 2003)*

More on H-Filter

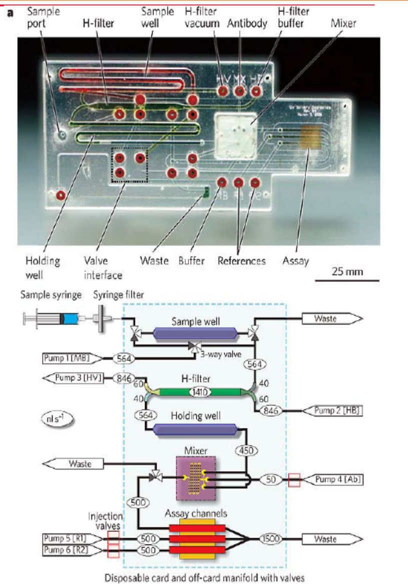
> **H-filter**
  - **Developed by Yager and colleagues at UWash in mid-90's**
  - **Being commercialized by Micronics**

> **An intrinsically microscale device**
  - **Uses diffusion in laminar flow to separate molecules**



Yager *et al.*, Nature 2006

Courtesy of Paul Yager, Thayne Edwards, Elain Fu, Kristen Helton,



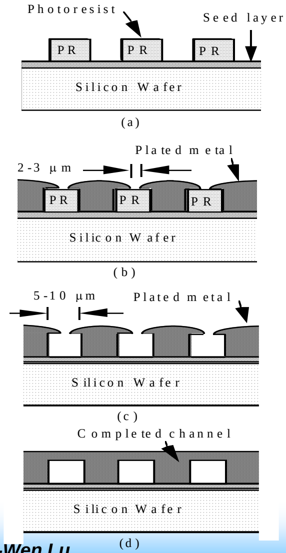
Courtesy of Paul Yager, Thayne Edwards, Elain Fu, Kristen Helton, KjellNelson, Milton R. Tam, and Bernhard H. Weigl. Used with permission.

Take Home Message

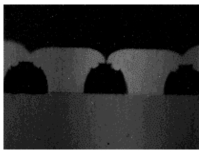
- Microchannel Fabrication
- Microchannel Functions:
  - Transportation
  - Mixing
  - Separation
- Pumps
- Active Mixing vs Passive Mixing
  - Hydrodynamic focusing
  - Why and how chaotic mixing?
- T-sensor (Y, H…etc)

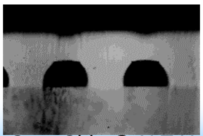
Sealing microchannels

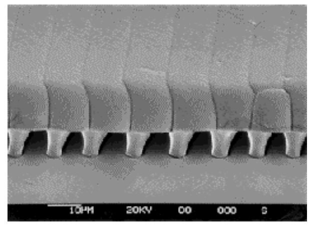
Self-sealing monolithic electroplated microchannel
Joo, Dieu, and Kim, MEMS '95



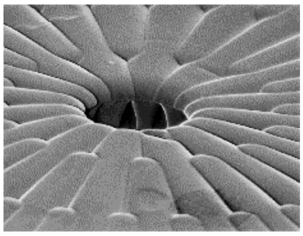
Advantages:
Low cost
Low temperature
IC compatible
Metal structure
e.g., as heater or cooling channels







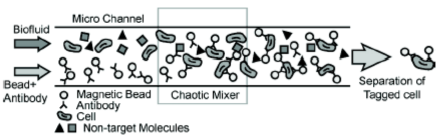
parallel channels
(width = 5-15μm, height = 8μm)

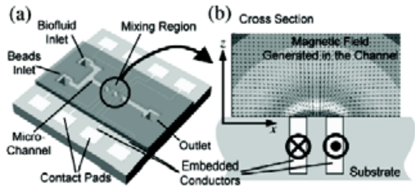


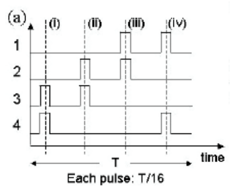
radially oriented channels

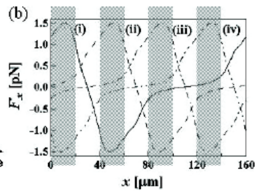
Active Chaotic Mixers

- Magnetic Force-Driven Actuation









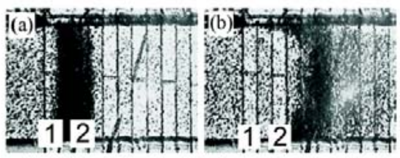
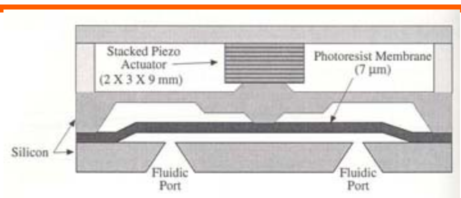


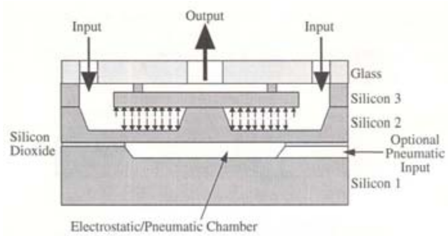
Fig. 4 Microscope images. (a) Beads are trapped between two conductors. (b) Beads are released when current is turned off.

Particles perturbation

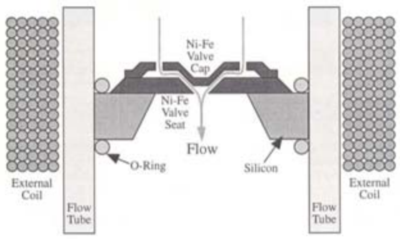
Other Valves



Micromachined piezoelectric valve (Shoji)

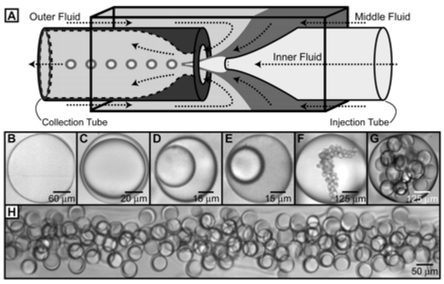


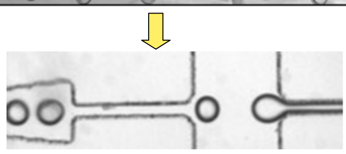
Micromachined electrostatic / Pneumatic valve (Huff)

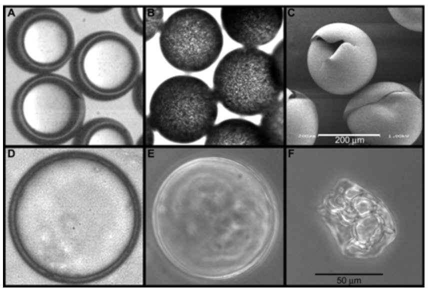


Micromachined electromagnetic valve (Shoji)

Microchannels by capillary tubes

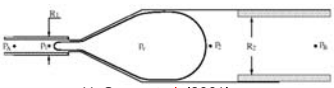




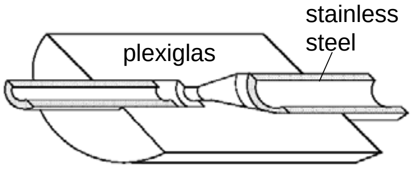


A microcapillary device for double emulsions. Utada & Weitz *et. al.*, *SCIENCE*, 2005,

A micropump by asymmetric bubble growth

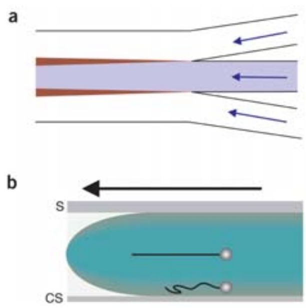


X. Geng *et al.* (2001)



The MEMS version by Dr. A. Lee's group @UCI

DNA in microchannels



Nature Methods - **5**, 517 - 525 (2008)