Microelectromechanical Systems (MEMs) Applications – Fluids

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OUTLINE

Introduction
What is a Fluid?
Basic Fluid Properties and Equations
Types of Flow
Bubbles
Capillary Forces
Fluidic Resistance
Fluidic Inductance
Flow Channels
Mixers
Gas Chromatograph

INTRODUCTION

Applications of Microfluidic Devices:

- Ink Jet Printers
- Chemical Analysis Systems
- Biological Sensing
- Drug Discovery
- Drug Delivery
- Molecular Separation
- Amplification, Sequencing, or Synthesis of Nucleic Acids
- Research tools

INTRODUCTION

Micro Fluidics Conference

Drug Discovery: High-throughput profiling of screening results, liquid chromatography library screening, a case study of a big pharma discovery operation's use of microfluidic screening technology and the acceleration of ion channel lead discovery.

Clinical Diagnostics: Case studies on the use of BioMEMS technology in two high volume diagnostics laboratories. The miniaturization and acceleration of diagnostic devices.

Drug Delivery: An exciting new applications field – hear about next generation fluidic microsystems used for localized therapy, including implantable biocapsules, microneedles, and electrophoretic patches.

Proteomics: Receive brand new results on applications in small molecule validation, biomarker discovery, toxicological studies, and mass spectrometry.

Sample Preparation: New fraction collection systems, integration of sample prep steps using channel structures, novel sample partitioning technology and reconfigurable field transport geometries.

Device Engineering and Microfabrication: Fluid handling in an integrated device. The integration of individual analysis components. Case studies of microdevice manufacturing techniques – including the engineering stage, production equipment, and post-production processes.

INTRODUCTION

Issue	Macroscopic	Micromachined
Unwanted turbulent flow?	Y	N
Very small dead volume?	varies	Y
Problems purging bubbles?	N	Y
Efficient liquid pumps available?	Y	not yet
Efficient liquid valves available?	Y	not yet
Efficient gas pumps available?	Y	N
Efficient gas valves available?	Y	Y
Simple interconnect scheme?	Y	N
Chemical resistant materials available?	Y	varies
Low power?.	N	varies
Sub-cm^2 volume?	N	Y
High surface-area-to-volume ratio?	N	Y
Batch fabricated?	N	Y (not packaging)

WHAT IS A FLUID?

A **fluid** is a material (gas or liquid) that deforms continually under shear stress. This simply means that the material can flow and has no rigid three-dimensional structure. Under most circumstances (exceptions include extremes in ambient temperature and pressure), liquids and gases may be treated identically, with the exceptions that gases generally need complete containment and that gases are generally **compressible**, while liquids are generally **incompressible**.

BASIC FLUID PROPERTIES - DENSITY

Density $\rho = m/V$ in Kg/m^3 or g/cm^3

Substance	Pressure	Density, kg/m^3
Water	1 atm	998
Water	50 atm	1,000
Seawater	1 atm	1,024
Ice	1 atm	917
Ethanol	1 atm	791
Acetone	1 atm	792
Air	1 atm	1.21
Air	50 atm	60.5
Mercury	1 atm	13,600
Iron	1 atm	7,900
Quartz	1 atm	2,650

Incompressible

compressible

IDEAL GAS LAW

PV = nRT

P = pressure, in Pa = N/m2
V = volume, in m3
N = number of moles (mol)
R = gas constant, 8.3151 N m / mol K
T = absolute temperature, in K

BASIC FLUID PROPERTIES

Pascal's principle is a statement of the fundamental concept that pressure applied to an enclosed fluid is transmitted to every portion of the fluid (and hence the vessel it is in), and applies whether or not the fluid is incompressible.

Archimedes' principle states that the buoyant force acting on an immersed body is equal in magnitude (but acting in the opposite direction) to the force of gravity on the displaced fluid.

Viscosity, µ, is a measure of how resistant a fluid is to flow (e.g., honey is more viscous than water) and is analogous to friction between solid objects (conversion of mechanical energy into thermal energy). Viscosity can be found to be given in many differing units in the literature, but the most common is the poise (g/(s-cm)).

VISCOSITY

Substance	Temperature (°C)	Viscosity (centipoise = 0.01 g/(s•cm))
Water	0	1.787
Water	20	1.002
Water	100	0.2818
Water Vapor	100	0.01255
Blood	37	4.5 to 5.5
Acetone	25	0.316
Ethanol	0	1.773
Ethanol	20	1.200
Isopropanol	15	2.86
Mercury	0	1.685
Mercury	20	1.554
Air	0	0.01708
Air	18	0.01827
Carbon Dioxide	0	0.01390
Carbon Dioxide	20	0.01480
Nitrogen	27.4	0.01781
Xenon	20	0.02260

BASIC FLUID PROPERTIES

Volume flow rate of a fluid, Q, in a channel is given by:

$Q_v = A\,v'$ in m^3/s

A is cross-sectional area and v' is average velocity

Mass flow rate is the product of the volume flow rate and the density of the fluid

$Q_m = A\,v'\,d$ in Kgm/s

BASIC FLUID PROPERTIES

Bernoulli's equation – for steady-state flow of an incompressible, frictionless fluid in a channel of varying dimension, the pressure and the velocity of the flow along a streamline (path of a fluid molecule or particle in steady flow). And for level flow (no effect of gravity due to height differences.

$$P_2 = P_1 + ½ \rho (v_1^2 - v_2^2)$$ where

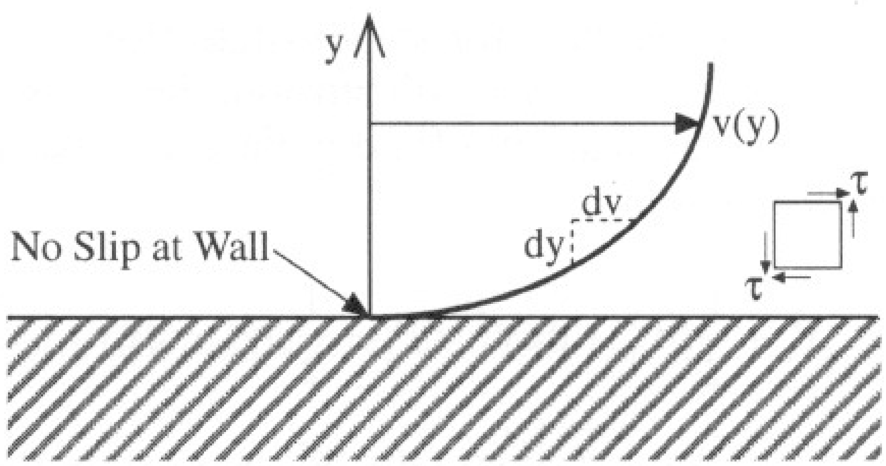
P_1 and P_2 are pressures at two points
v_1 and v_1 are velocities at two points

BASIC FLUID PROPERTIES

Newtonian Fluids, a shear stress, τ, is linearly proportional to shear rate, with the proportionality constant being the viscosity, μ,

$$\tau = \mu \, dv/dy$$

where y is the distance measured normal to the surface of a flow channel



TYPES OF FLOW

1. **Laminar flow** – velocity of a given point in the fluid does not change with time, well defined, stable stream lines.
2. **Turbulent flow** – above not true.

Reynolds number (Re) – indicates the relative turbulence of a flow stream

$$\mathbf{Re = \rho\ v\ Dh / \mu}$$

where Dh is the hydraulic diameter, in m

If Re is ~ > 2300 then the flow might be turbulent

FORMULAS FOR HYDRAULIC DIAMETER

Cross Section	Formula	Variables
Circle	$D_h = D$	D = diameter
Annulus	$D_h = (D - d)$	d = inner diameter
Rectangle	$D_h = \frac{2ab}{(a+b)}$	a, b = sides
Triangle, equilateral	$D_h = \frac{\sqrt{3}}{3} a$	a = side
Triangle, general	$D_h = \sqrt{\frac{16s(s-a)(s-b)(s-c)}{(a+b+c)}}$ where $s = \frac{1}{2}(a+b+c)$	a, b, c = sides

EXAMPLE

$Re = \rho\ v\ Dh\ /\ \mu$

Water flowing through a circular flow channel of 500 µm in diameter with a velocity of 100µm/sec. Determine at what diameter the flow becomes turbulent. ρ = 998 Kg/m^3, μ = 1.0 centipoise (g/sm)

Re = (998 Kg/m^3) (100E-6 m/s)(Dh)/(1g/s-m)(1Kg/1000g)
= 100,000 Dh
2300 = 100,000 Dh

So Dh greater than 2.3 cm is needed for turbulent flow

BUBBLES IN MICROSTRUCTURES

Bubbles can be eliminated by priming a fluidic system with a gas that is highly soluble in water, like CO2, C2H2, H2S, SO2 or NH3. Then fill with water and the bubbles are absorbed in the water.

CAPILLARY FORCES

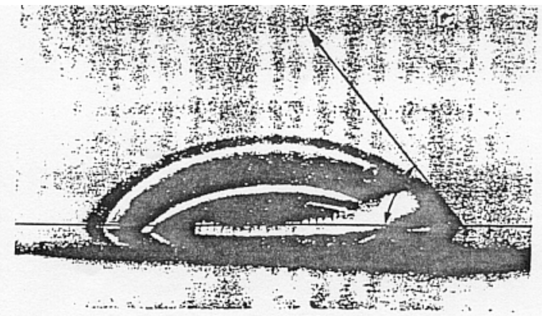
Assuming a round channel the capillary force is:

$$F1 = 2 \pi r \gamma \cos(\Theta)$$

where Θ is the contact angle
γ is the interfacial surface tension

Gravitational force in a vertical capillary:

$$Fg = \rho g \pi r^2 h$$



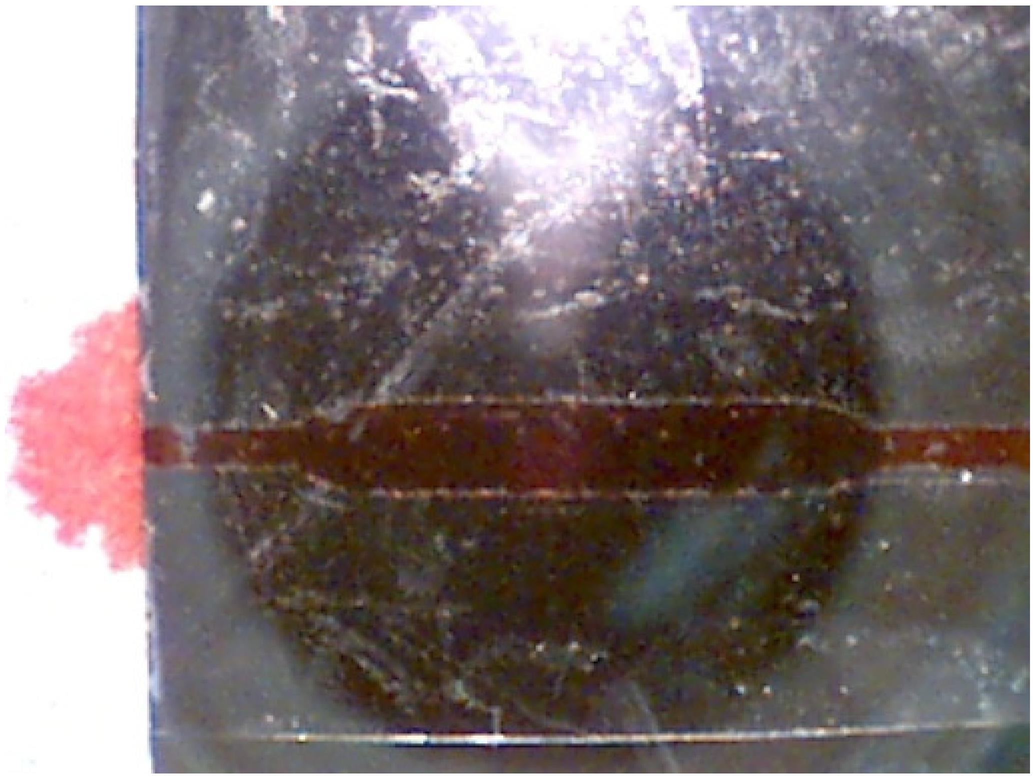
Contact angle measurement of a water drop on a silicon surface

(A) RCA clean
$NH_4OH:H_2O_2:H_2O$ = 1:1:6 for 10 min at 75 °C,
$HCl:H_2O_2:H_2O$ = 1:1:6 for 10 min at 75 °C,
(B) $H_2O:H_2O_2:NH_4OH$ = 6:1:4 for 10 min at 55 °C
(C) RCA clean and 65% HNO_3 for 10 min
(D) RCA clean and 2% HF for 10 min
(E) $H_2SO_4:H_2O_2$ = 5:1 for 10 min
(F) 30% H_2SO_4 for 10 min
At the end of the pretreatments the wafers were always rinsed in deionized water.

pretreatment	direct after pretreatment	5 h	27 h	3 d	6 d
A	4.5°	5.5°	9°	16°	20°
B	5.5°	4°	5.5°	7.5°	12°
C	1°	4°	4°	12.5°	16.5°
D	52°	61°	63.5°	59.5°	57°
E	1.5°	4°	6°	17°	22°
F	51°	46°	45°	47.5°	45°

FLUID CHANNEL MADE AT RIT

Flow in this fluid channel is totally by capillary action.



Movie

FLUID RESISTANCE

Fluidic resistance is defined as the ration of pressure drop over flow rate:

$$\mathbf{R = \Delta P/Q}$$

For a circular channel $R = 8\ \mu\ L\ /\ \pi\ r^4$

For a rectangular channel $R = 12\ \mu\ L/\ w\ h^3$

FLUID CAPACITANCE

Fluids can have a capacitance related to its change in volume with change in pressure

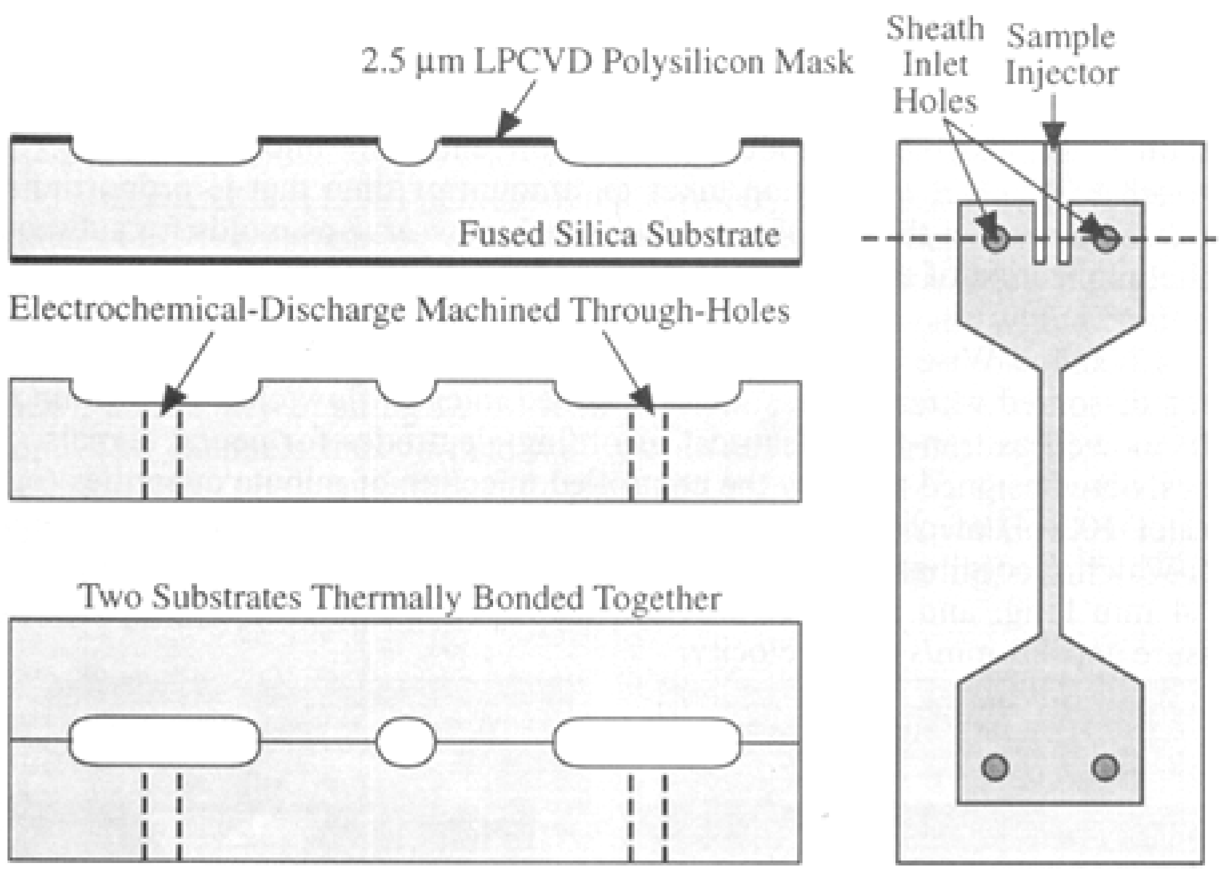
$$C = dV/dP$$

FLUID INDUCTANCE

Fluids can have an inductance related its inertia.

$$\Delta P = H\, dQ/dt$$

FLOW CHANNELS



Micromachined flow cytometry cell showing process cross section (left) and top view (right). Sheath fluid is injected into the holes perpendicular to the flow path, and the sample is injected parallel to the flow path. After Sobek, et al. (1994).

FLOW CHANNELS

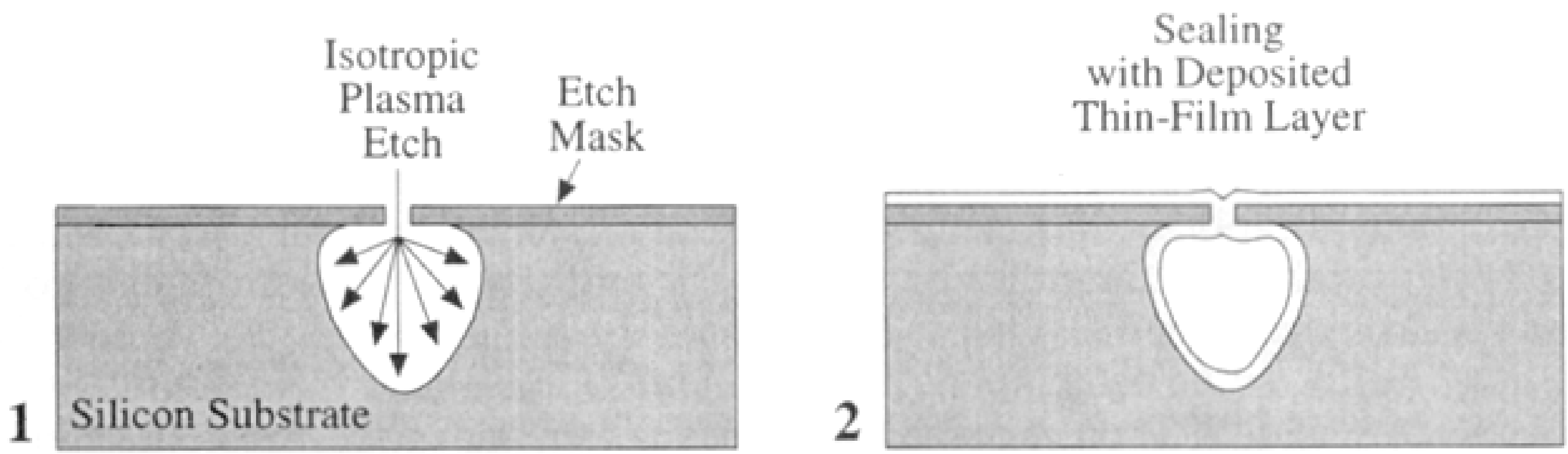


Illustration of bulk micromachined fluidic channels fabricated by etching isotropically through a "slit" mask and then sealing the channel with a deposited thin-film layer. After Flannery, et al. (1997).

FLOW CHANNELS

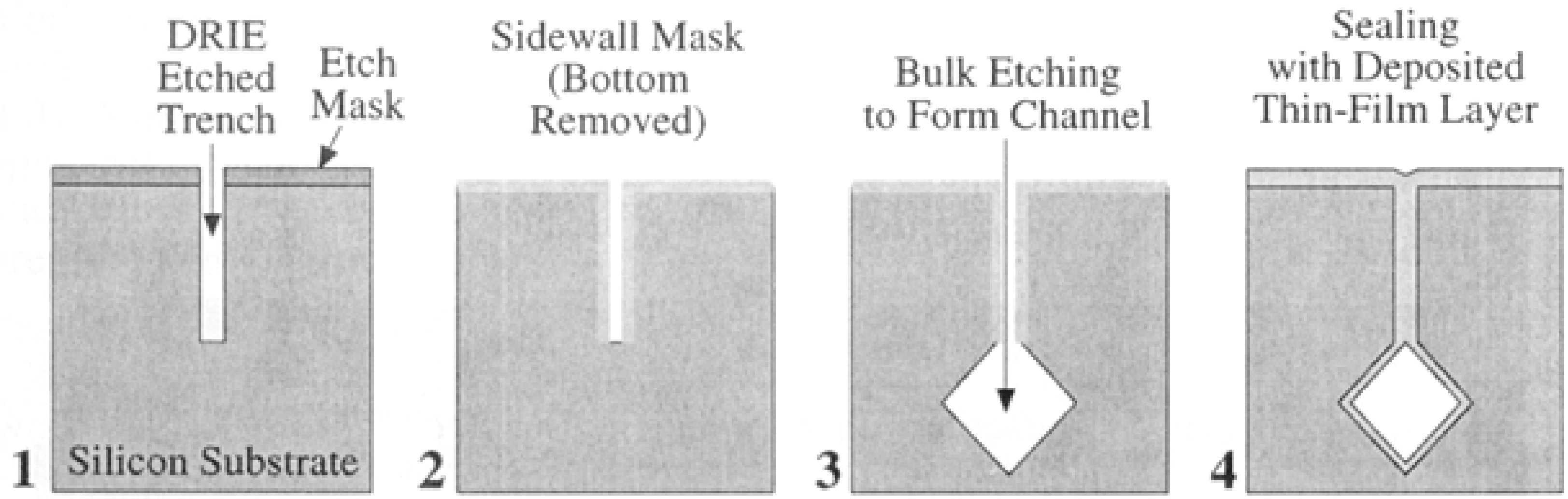
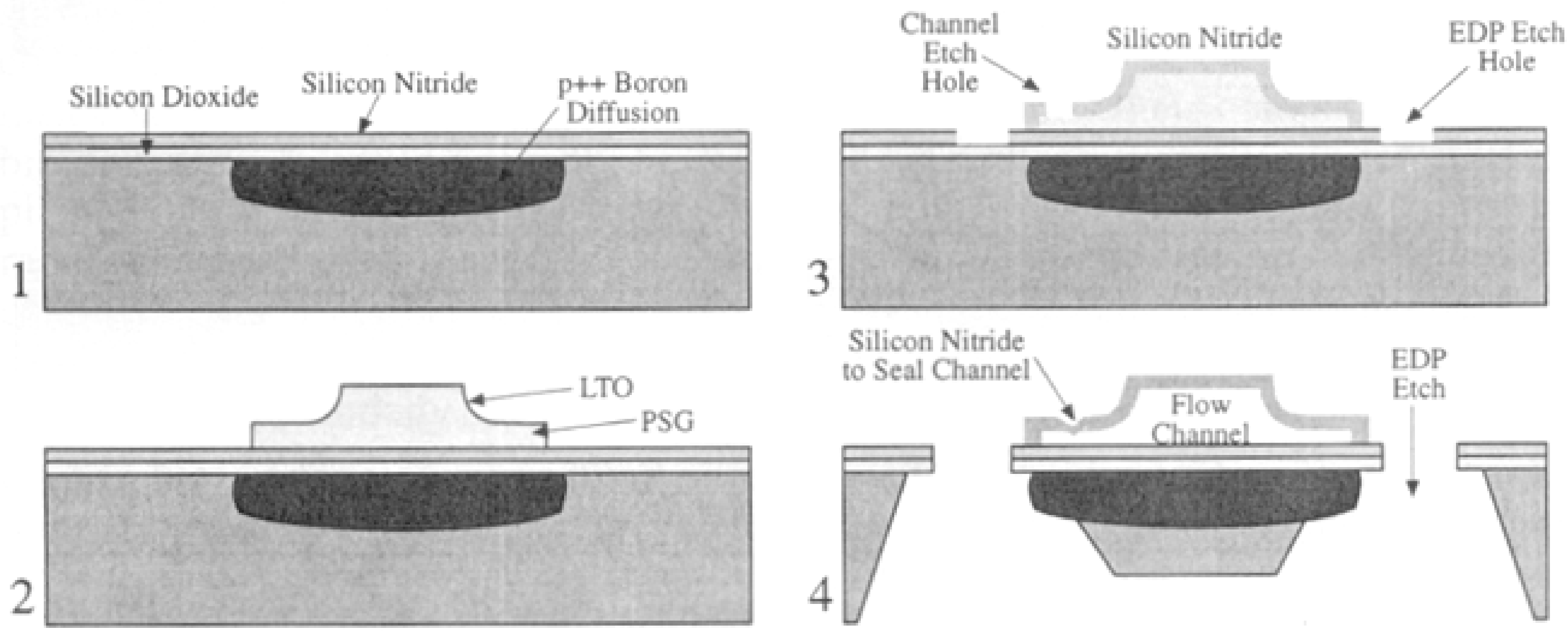


Illustration of a process for forming buried, bulk-etched fluidic channels in a silicon substrate, and subsequently sealing them with a deposited thin-film layer. Adapted from Tjerkstra, et al. (1997).

FLOW CHANNELS



Surface micromachined flow channel process. After Lin, et al. (1993).

FLOW CHANNELS

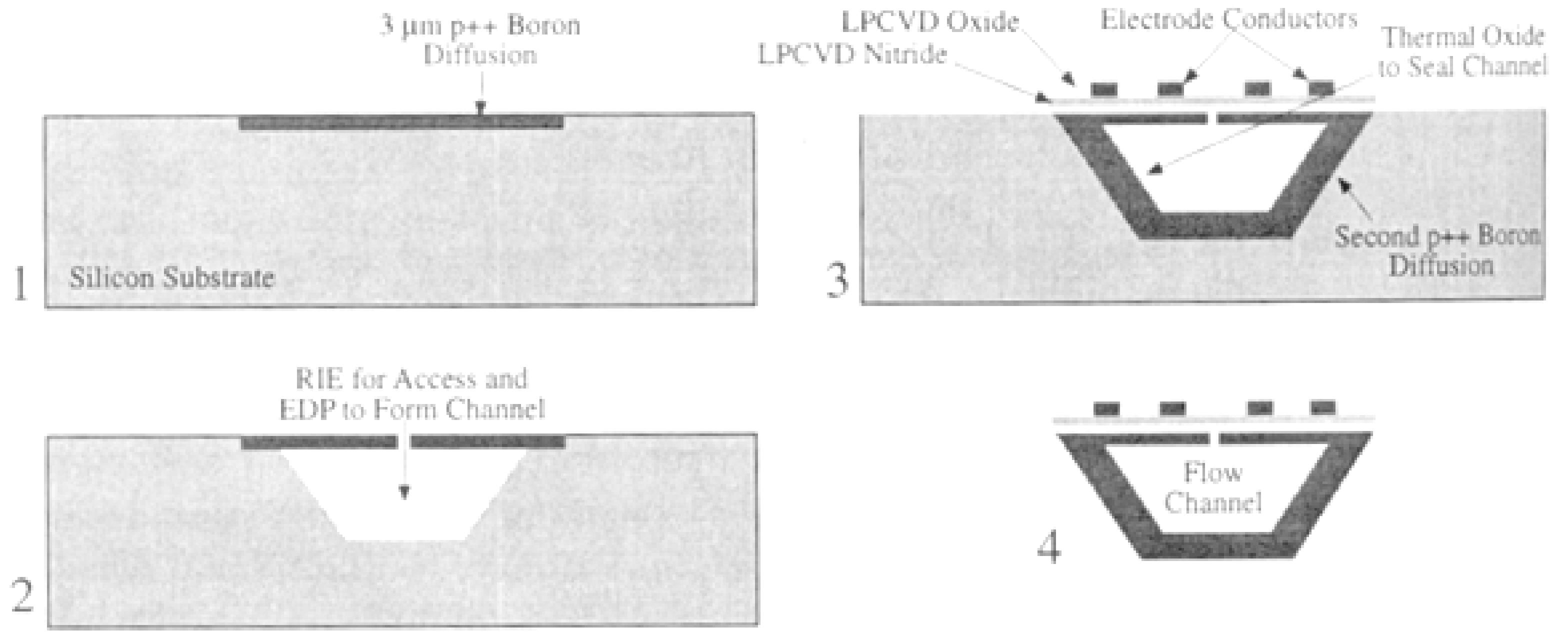
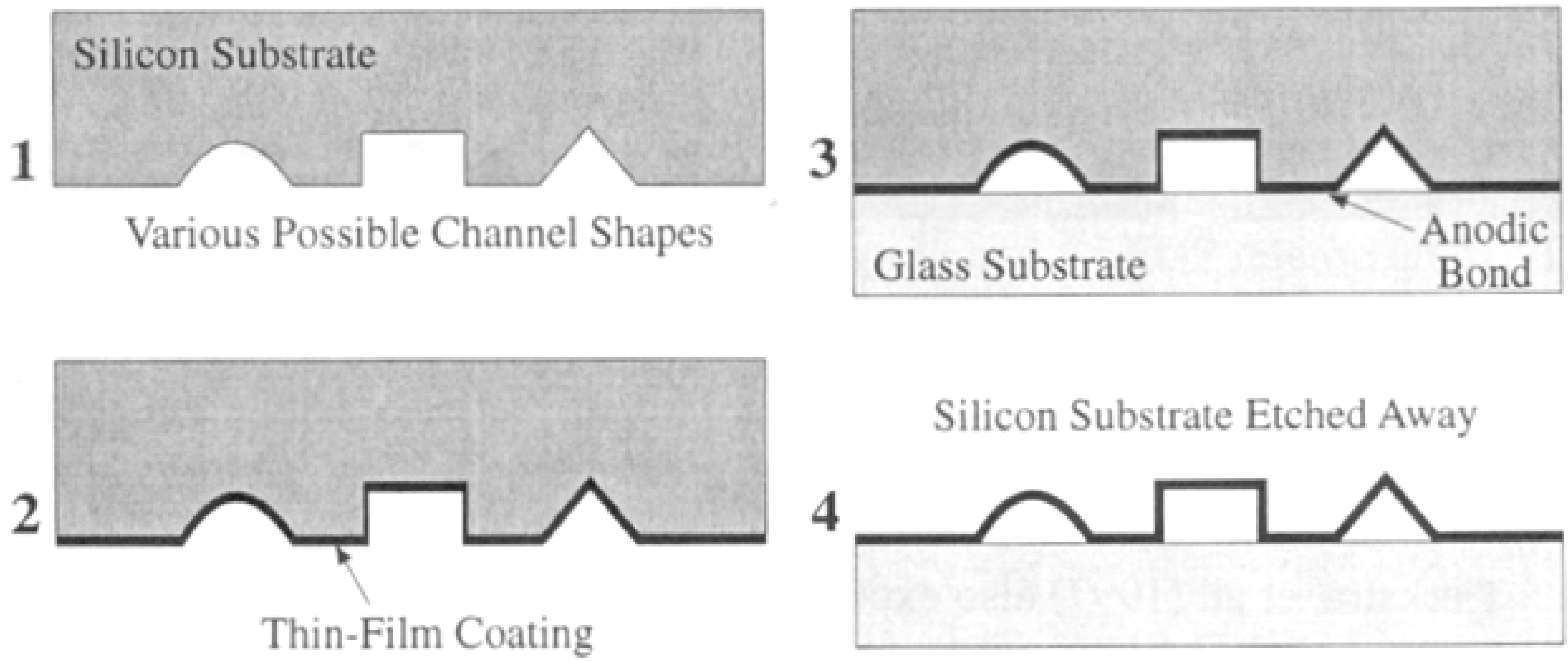


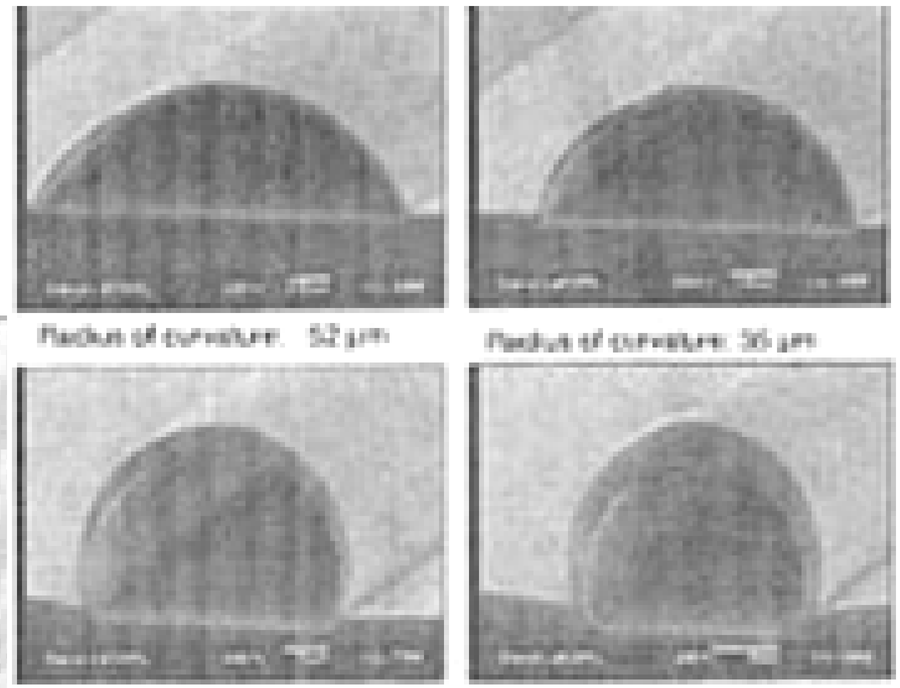
Illustration of flow channel process. After Chen and Wise (1994).

FLOW CHANNELS



FLOW CHANNELS

Photoresist, reflow, oxide, coating, Acetone removal

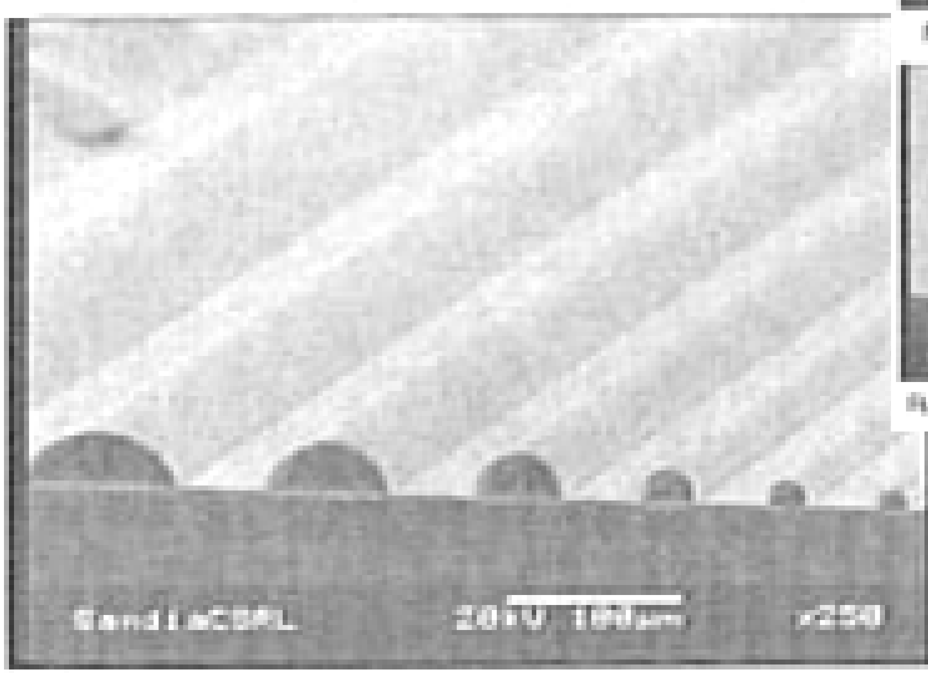


Radius of curvature: 52 µm

Radius of curvature: 35 µm

Radius of curvature: 15 µm

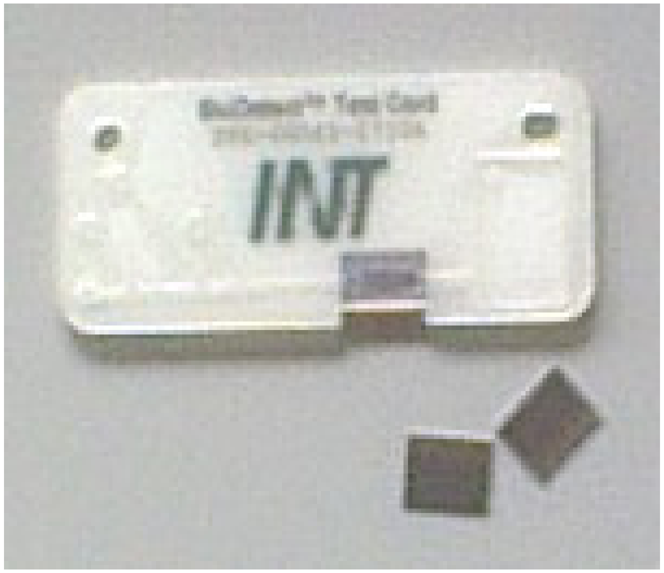
Radius of curvature: 8 µm



Microscopic views of raised, hemispherical canals ranging from 8 to 100 µm in diameter

FLOW CHANNELS

Laminated layers of plastic with laser cut channels and devices.



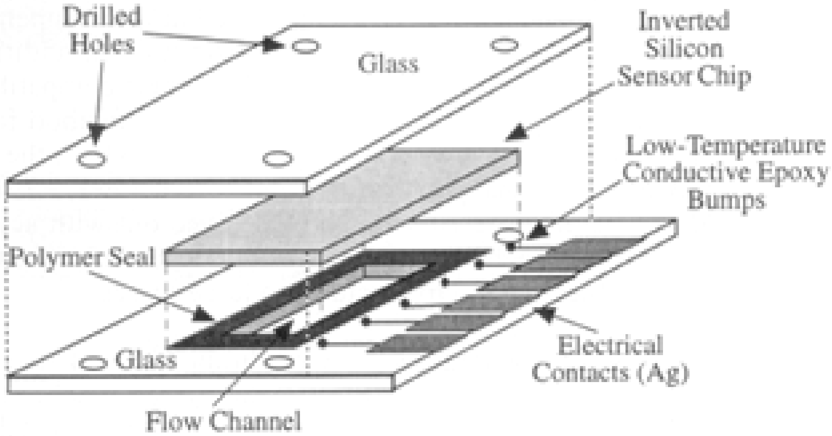


Illustration of a technique for integrating micromachined structures into assembled fluidic systems. After Poplawski, et al. (1994).

MIXING

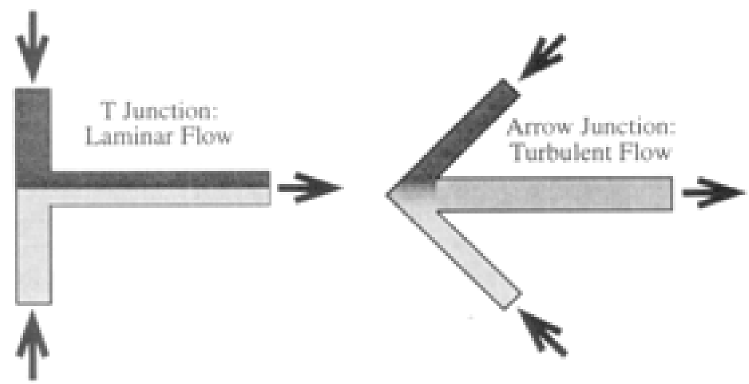


Illustration of shapes that can be used to enhance mixing at macroscopic scales. After Krulevitch (1995).

Another approach is to force flow around a turn with a small radius of curvature, which induces a secondary, rotating flow due to centripetal acceleration (although laminar flow can redevelop after the turn for small values of R).

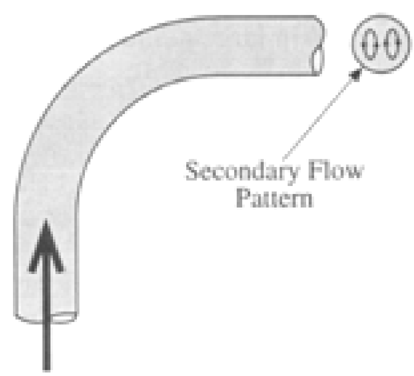


Illustration of centripetal mixing during fluid transit around a corner. After Krulevitch (1995).

FLOW CHANNELS

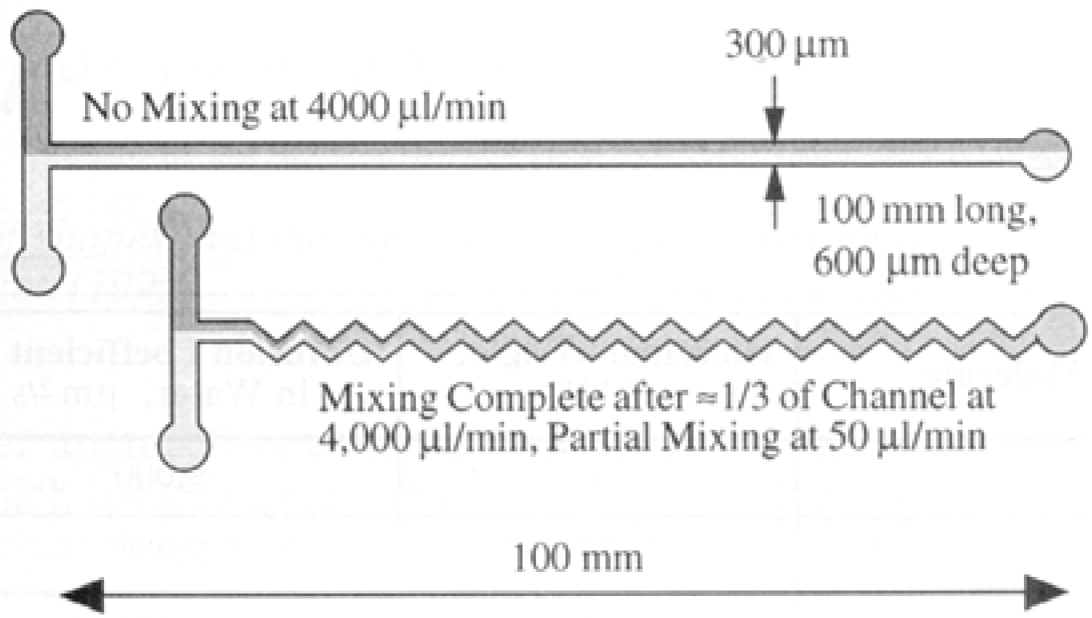
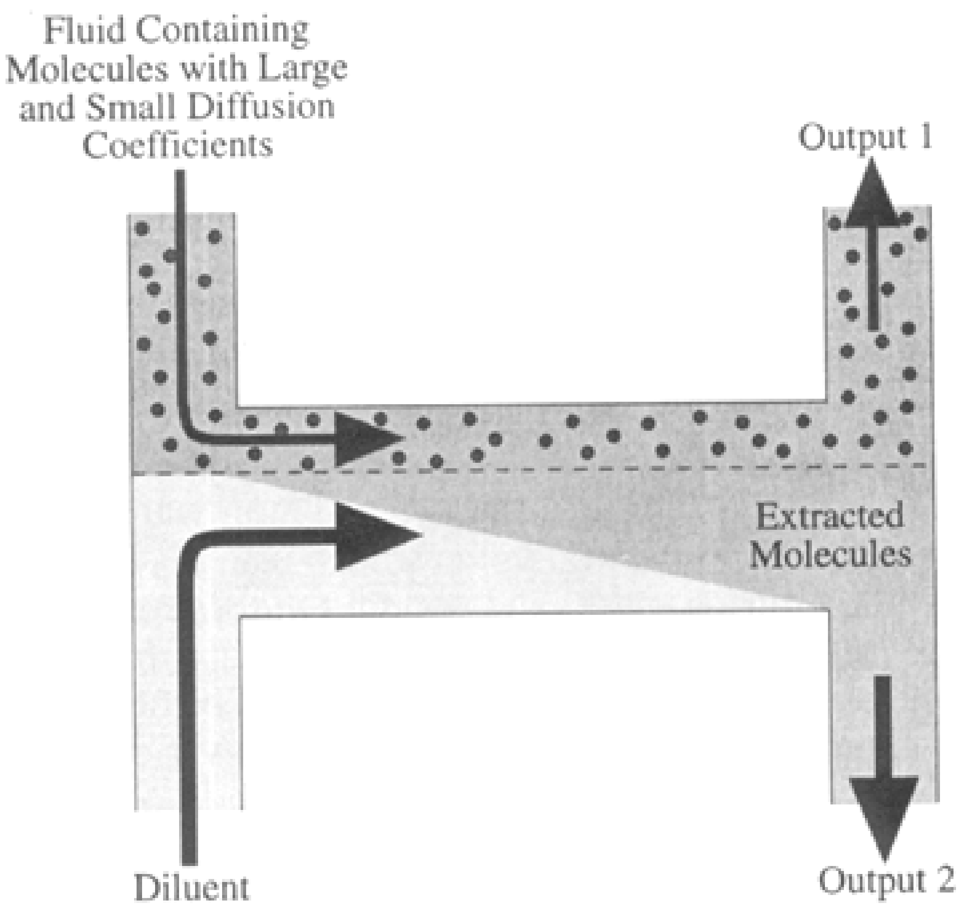


Illustration of miniature fluidic channels used to compare mixing in macroscopic and microscale fluidics. After Branebjerg, et al. (1994).

H FILTER


Fluid Containing Molecules with Large and Small Diffusion Coefficients
Output 1
Extracted Molecules
Diluent
Output 2

Chromatography

Glass gas chromatography chip for environmental testing

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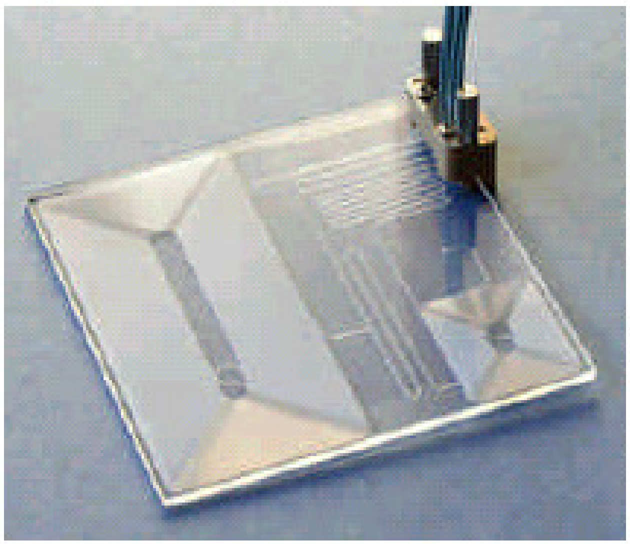
Tuesday, February 16, 2010



Dolomite, in collaboration with the UK's National Center for Atmospheric Science, has successfully tested the miniaturization of gas chromatography equipment for environmental testing. The glass Gas Chromatography Chip has a 300 µm thick layer and is fabricated with isotropic channels, which replace the capillary and spindle structure which is characteristic of standard GC columns. This microfluidic miniaturization enables the production of portable and low power GC systems suitable for environmental applications such as atmospheric monitoring.

The chip design includes an injection zone, which allows activated carbon particles to be loaded and held, forming a sample absorption column. Closely packed within a 100 x 100 mm microfluidic chip, the 7.5 m and 1.4 m long channels have an internal diameter of 320 µm to ensure efficient heat transfer. With a circular cross section, a uniform coating can be evenly applied to the inside surface of the channel, effectively mimicking the stationary phase, to aid separation.

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2. IEEE Journal of Microelectromechanical Systems.

HW – APPLICATIONS FLUIDS

1. none