MICROFLUIDICS DEVICES and MICROSYSTEMS

Technologies and Perspectives

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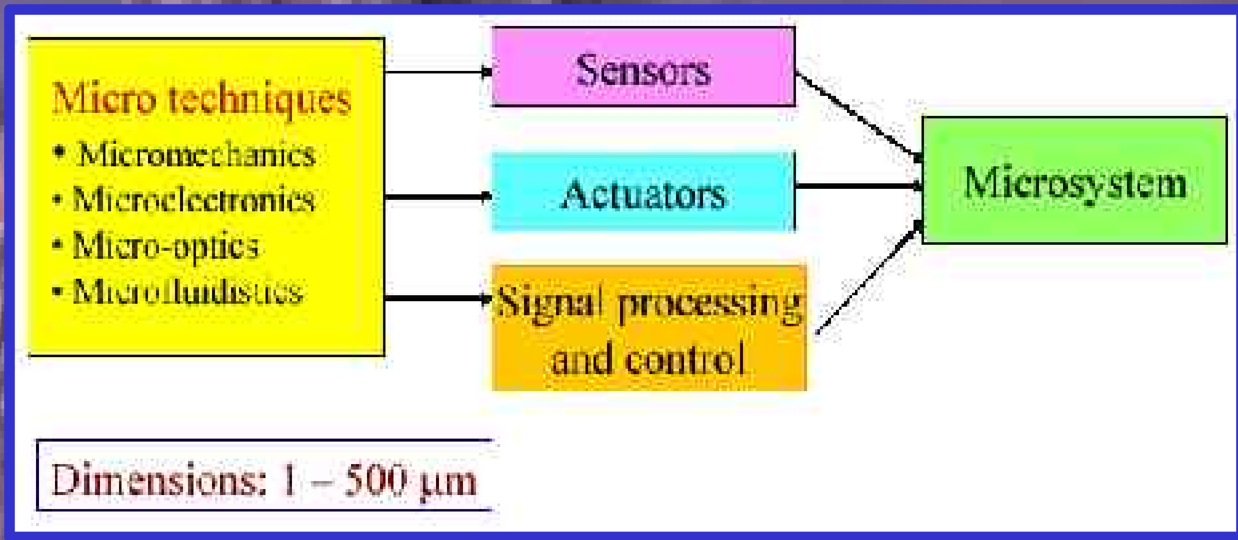
Outline

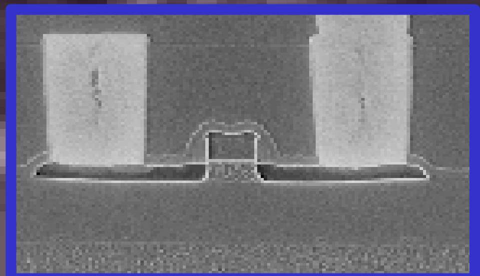
- Micro-Electro-Mechanical-Systems (MEMS)
- Scaling Effect
- Fabrication Methods
- Microfluidics Devices
- Gas Contamination Pre-concentrators
- Flow and Gas Microsensors
- Fluidic Logic
- FIA
- Conclusions

Micro-Electro-Mechanical-Systems (MEMS)

Components like sensors, actuators, electronics integrated on a single chip.



- Analytical Chemistry
- Biotechnology
- Pharmaceutical
- Information Technology
- Telecommunications
- Aerospace
- Defense
- Automotive



Micromachining & Microelectronics

Microfluidics

Microfluidics refers to fluid flow in microchannels as well as to microfluidics devices (pumps, valves, mixers, etc.) and systems. One of the dimensions of flow is measured in µm: e.g. channel.

Microfluidics Devices + Interfaces + Microstructures + ...

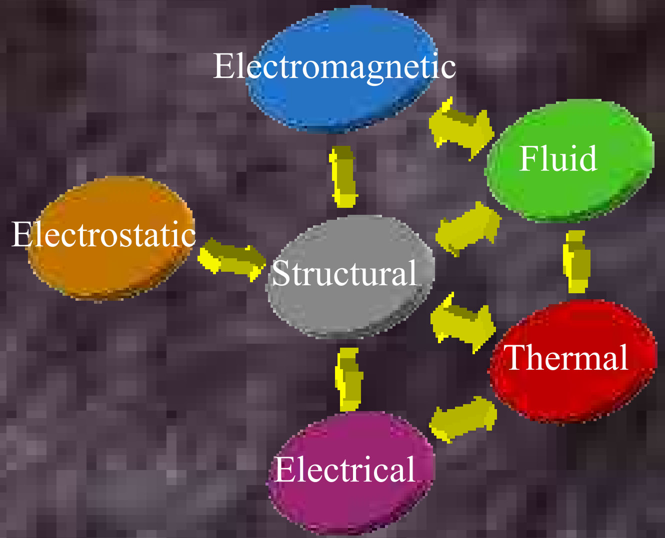
Microchannels	Pumps	Logic Devices
Critical Orifices	Valves	Mixers
Liquid Cooling Devices		Many Others

↓

Microfluidics Systems

Microfluidics - Why study it?

- Reduction in size
- Control of small amount of fluids
- The reduced consumption of reagents
- The capability of building integrated systems
- Reduction of power consumption
- Parallel devices + faster processes = high throughput
- Safety
- Reliability
- Integration + multifunctionality
- Portable devices
- User friendly devices



Microfluidics

Phenomena Components Systems Applications

Questions about microfluidics models

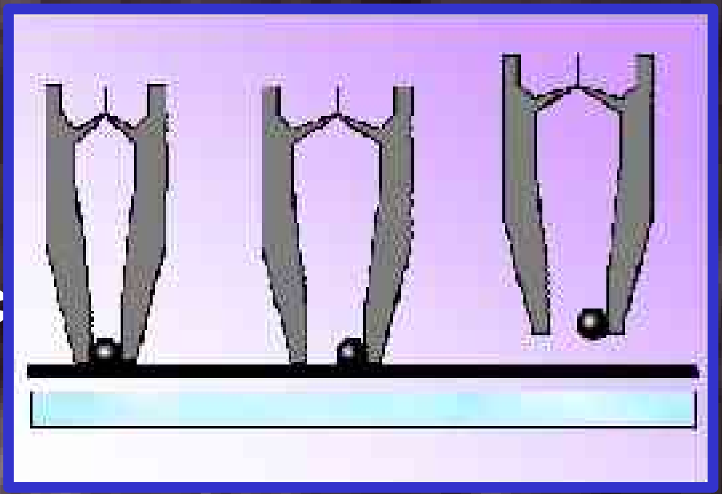
Scaling? Continuum assumption?

Surface forces? Others issues?

Scaling effect

Physical phenomena ≠ Macro world

Adhesive forces (van der Waals forc electrostatic forces, surface tension are more dominant than gravity in microworld.



Reynolds Number

$$Re = \frac{inertial\ \ forces}{viscous\ \ forces}$$

Inertial forces: ρ x v [2] x D² Viscous forces: μ x v x D

Where: ρ = density, v = flow speed,

D = hydraulic diameter, and μ = viscosity

Turbulent (Re > 2300) *depends of geometric configuration and roughness

1. In fluidics, assume two round pipes with the same flow situation, same Reynolds number

$$\Delta p = C_1 \frac{1}{r^2}, \quad C_1 = \text{constant}$$

Loss of pressure becomes **much larger** in microchannels *(r small)*

2. Required power

$$P = C_2 \frac{1}{r}, \quad C_2 = \text{constant}$$

Required power becomes **larger** in microchannels *(r small)*

3. In microchannels Reynold's number tends to be small.

This implies **laminarity** of flow

Liquids

Water (3 mm, 650 mm/s)

Re = 2000

Water (100 μm, 0.4 mm/s)

Re = 0.04

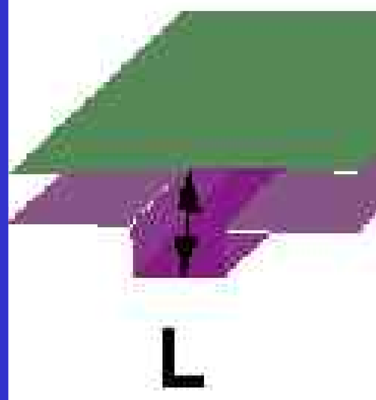
Gases

- = Macro dimensions
- (~ D > 10 μm)
- Chocked flow (M = 1)

is possible in laminar regime

Knudsen Number

(ratio of the mean-free-path to a characteristic dimension)



$$Kn = \frac{\lambda}{L}$$

Continuum	($Kn < 0.01$)
Slip Flow	($0.01 < Kn < 0.1$)
Transition Flow	($0.1 < Kn < 10$)
Free Molecular	($Kn > 10$)

Knudsen number characterizes for gases.

Continuum hypothesis holds better for liquids than gases.

In microworld continuum assumption seems to hold reasonably well. Breaks in nanoworld. Need molecular dynamics.

Simulations

Several different regimes of fluid mechanics and dynamics:

- Viscous flow vs. inviscid flow
- Steady vs. unsteady flow
- Laminar vs. turbulent flow
- Incompressible vs. compressible flow
- Open vs. confined flow

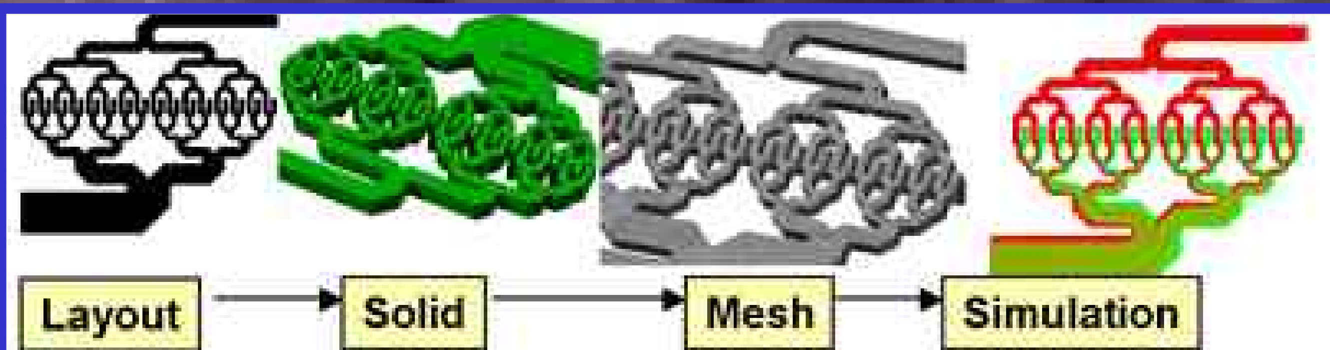
Most relevant to microfluidics:

Viscous, steady, laminar, incompressible flow.

In open flow, must worry about surface tension, surface chemistry effects.

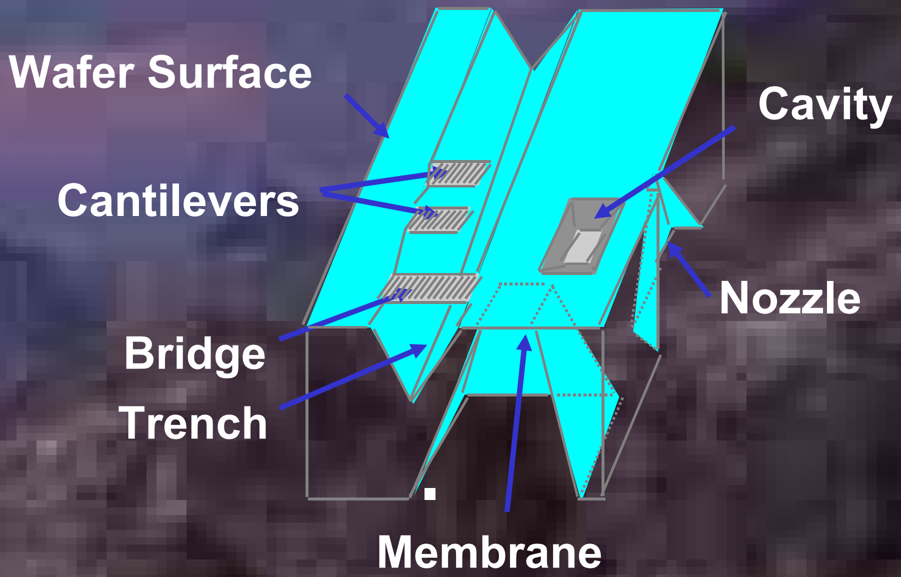
Multiphysics - ABAQUS, ANSYS, MEMCAD, COSMOS

Computational Fluid Dynamics (CFD) - FLOW-3D, ANSYS(FLOTRAN), N3S, CFD-ACE, FLUENT, CONVENTOR

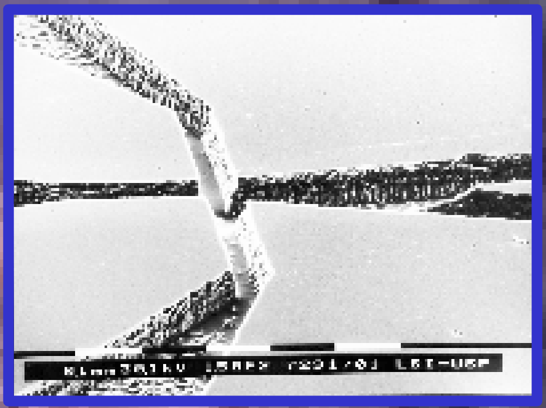


Multiple Fabrication Methods in Various Stages of Development

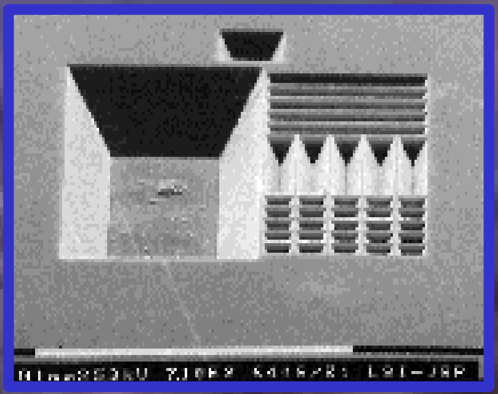
- Conventional micromachining
- LIGA
- Lamination and stamping
- Rapid prototyping methods
- Laser micromachining
- Biomimicry methods (molecular self-assembly)
- Other nanoassembly (scanning tunneling microscopy and atomic force microscopy)



Bulk Micromachining



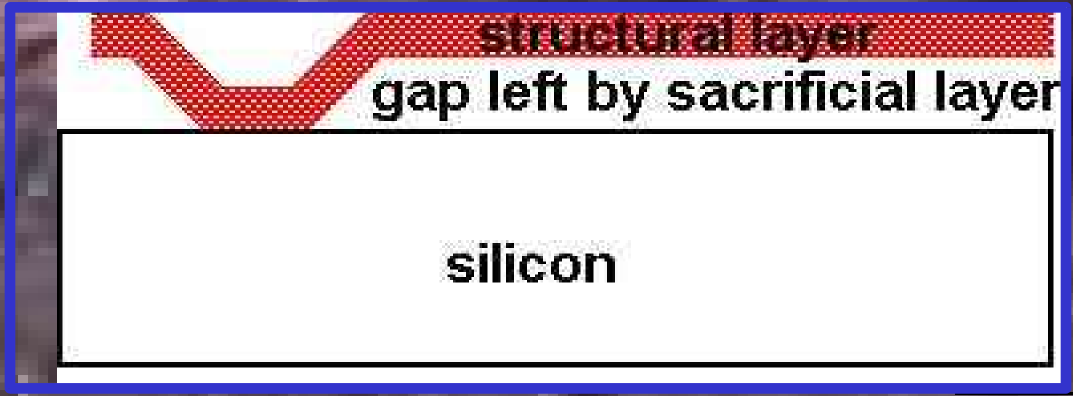
Plasma etching



Wet etching

Silicon-glass bonding

Surface Micromachinng

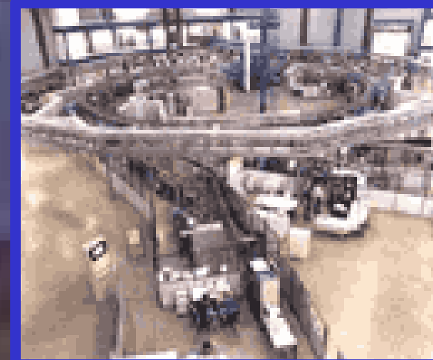


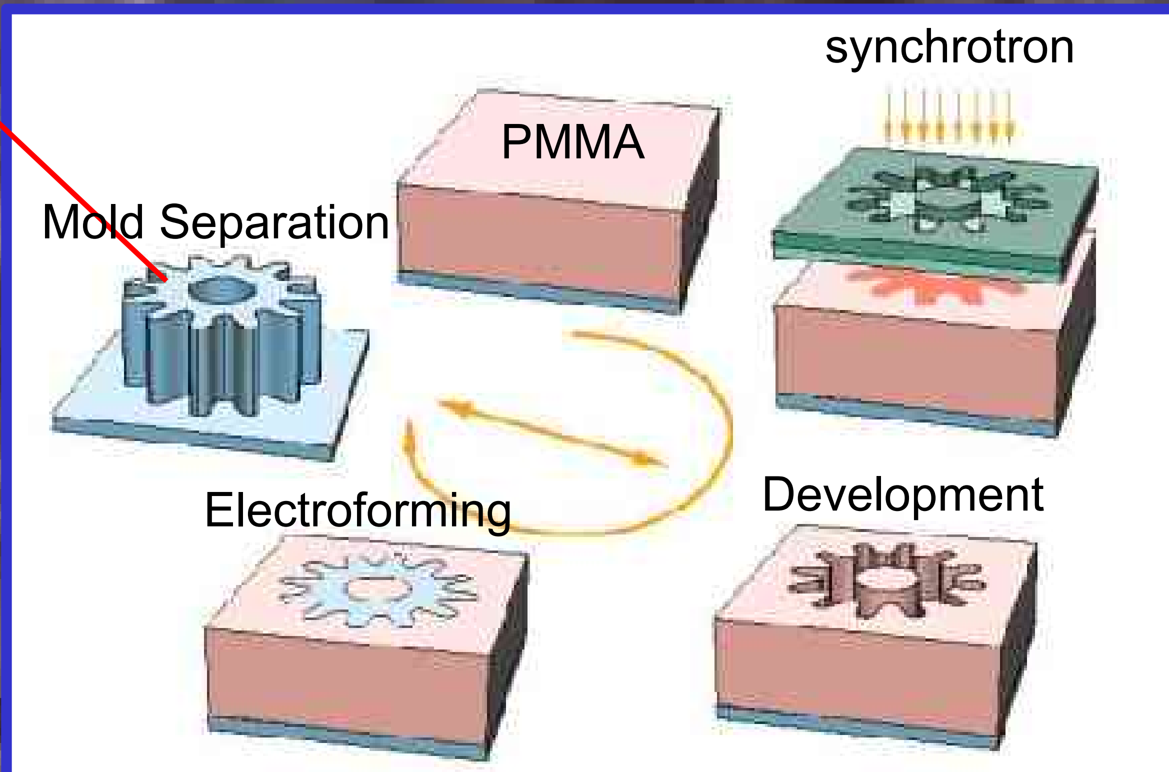
Sacrificial layer technology

LIGA technology

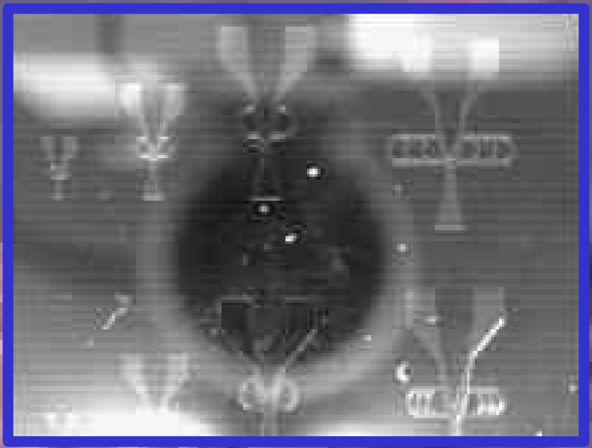
Lithographie, Galvanoformung, Abformung

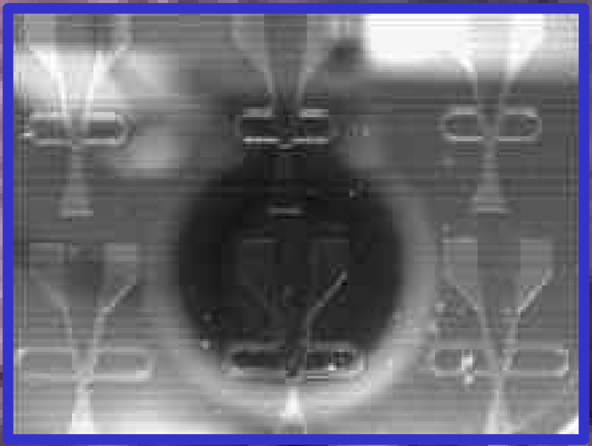
500 µm



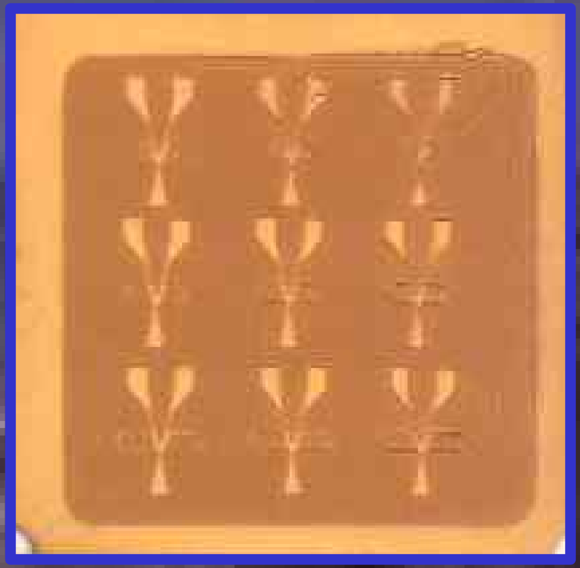


LIGA/UV Technologies





SU-8 / Silicon



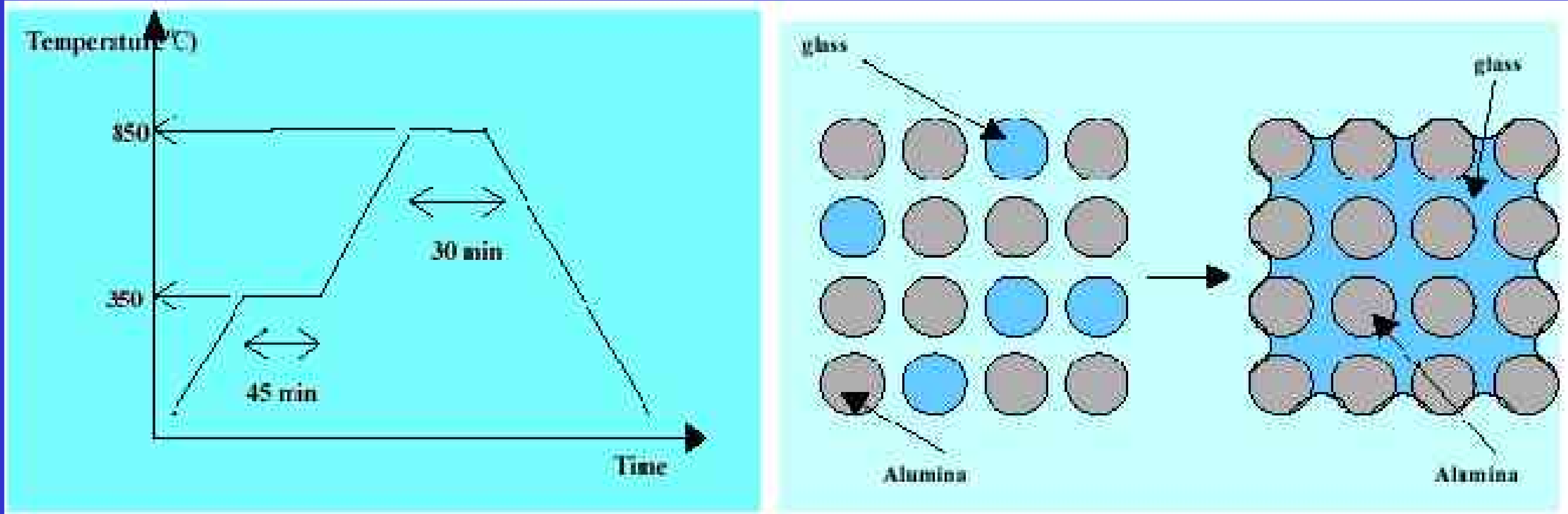
2 cm

SU-8 / Alumina

PGMEA (propyleneglycol monomethylether acetate)

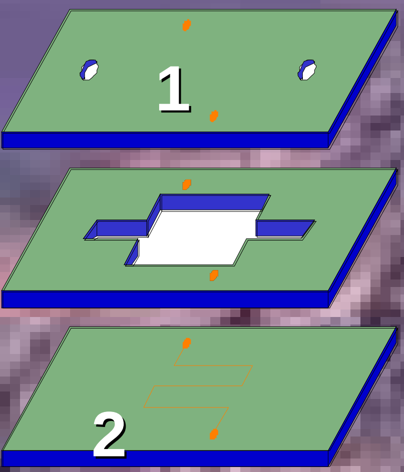
Low Temperature Co-Fired Ceramics (LTCC)

- Green ceramic tapes (manipulated at the green stage before sintering)
- Glass-ceramic composite materials
- Alumina (Al_2O_3) + Glass frit + Organic binder



Temperature profile and sintering model for LTCC materials

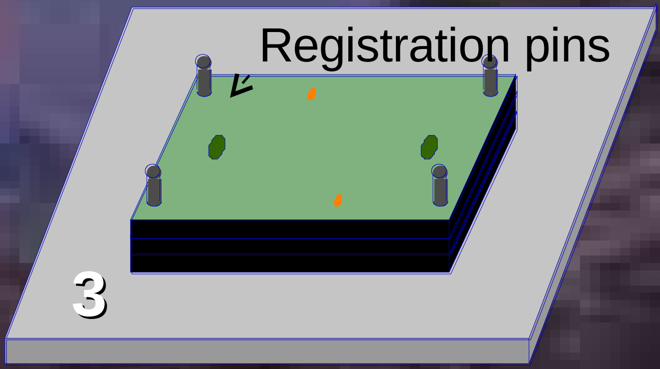
Flexible Layered Manufacturing of Meso-scale Systems Using Ceramic Tapes



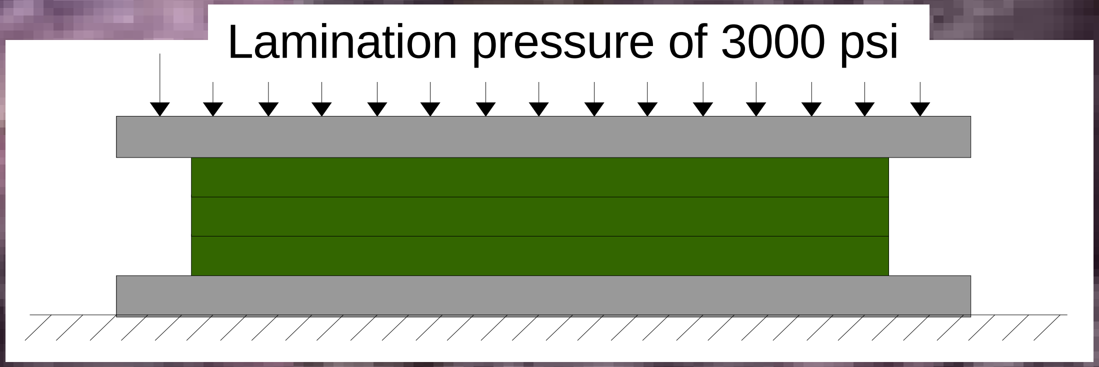
1. Machining each layer to create desired patterns

2. Screen printing and via filling or thin film deposition through a mask

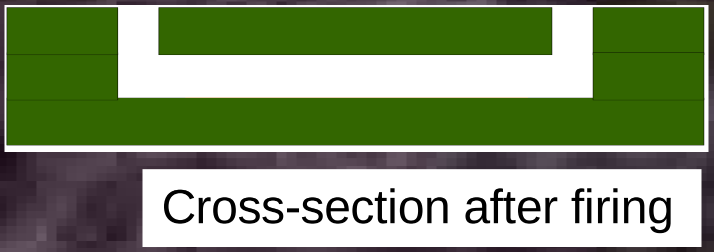
3. Alignment and Stacking



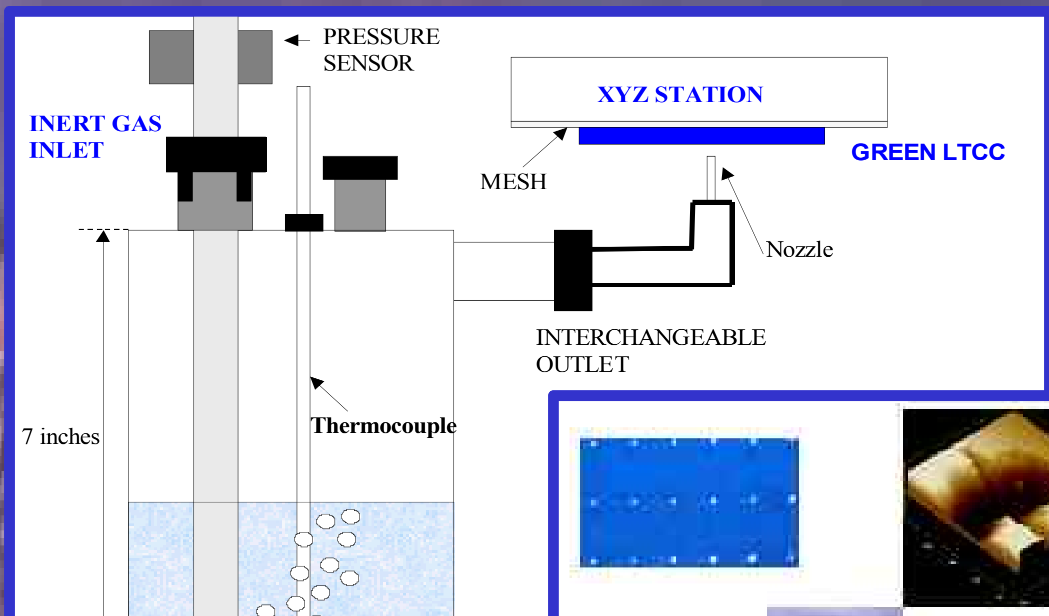
4. Lamination

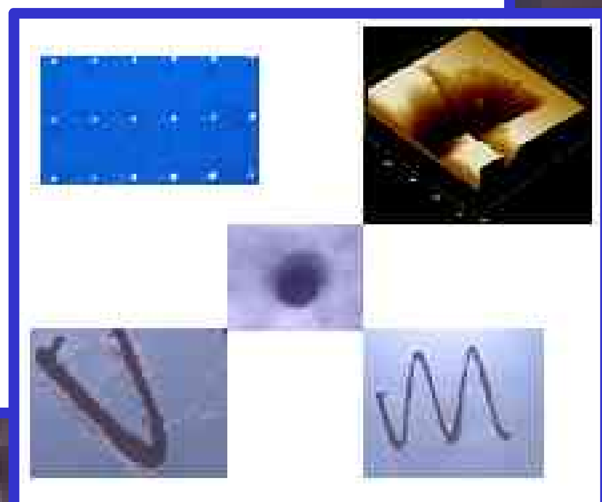


5. Co-firing



Vapor Jet Etching (VJE)





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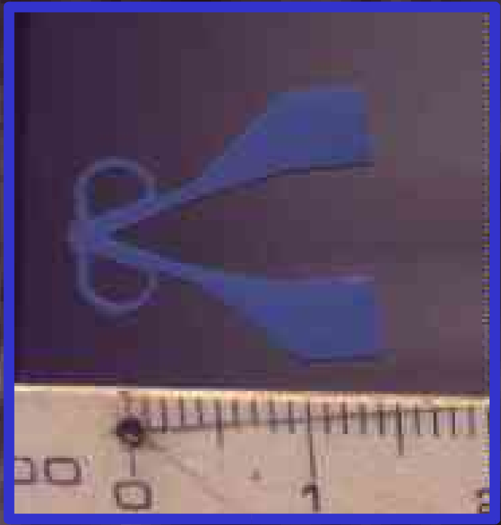
- Minimum diameter: 25 µm (PENN)
- Minimum diameter: 10 µm (UPR)

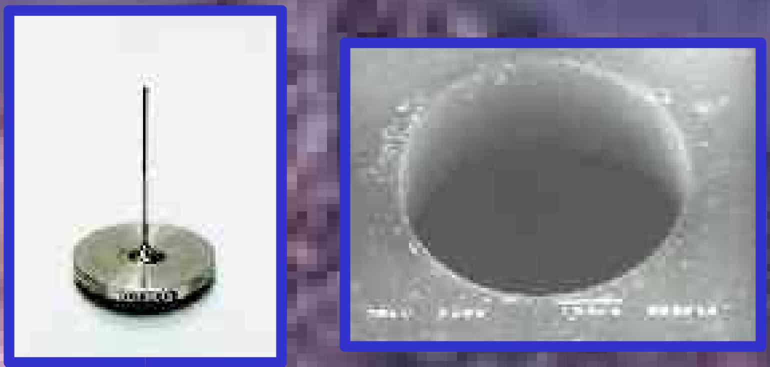
CNC Process

Microstructures in Acrylic



Mold in LTCC

Microfluidics Examples



Critical orifices

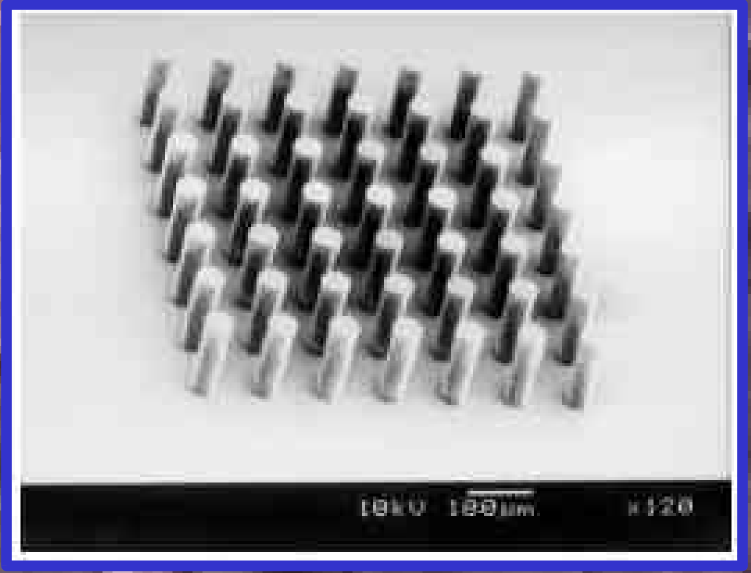
Heavy metal monitoring

Microfluidic amplifier

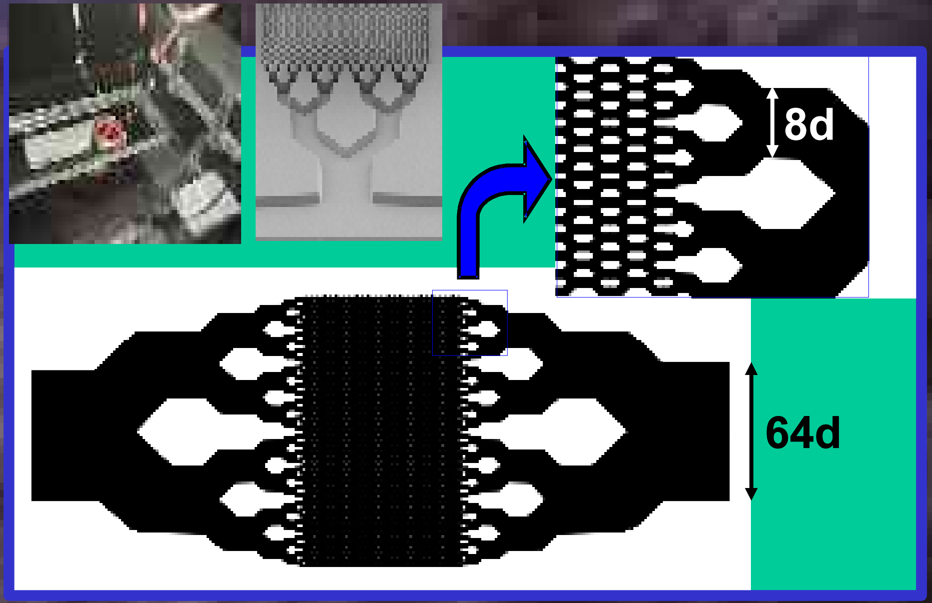
Micro flow oscillator

Microfluidics Examples

Hydraulic Micromotor

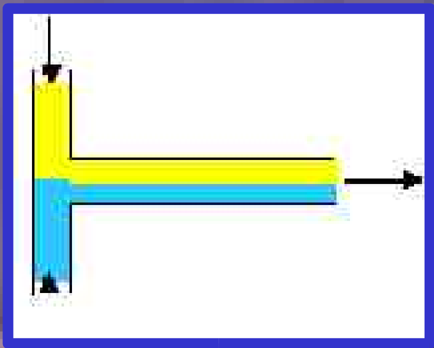


Microfilter for Liquids

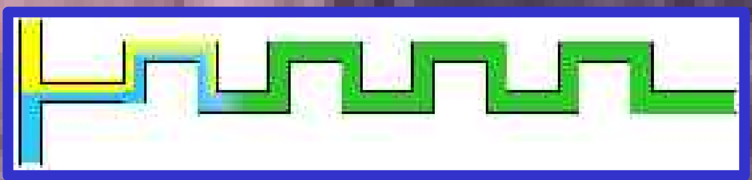


Pre - Concentrator

MEMS Fluid Mixing Schemes



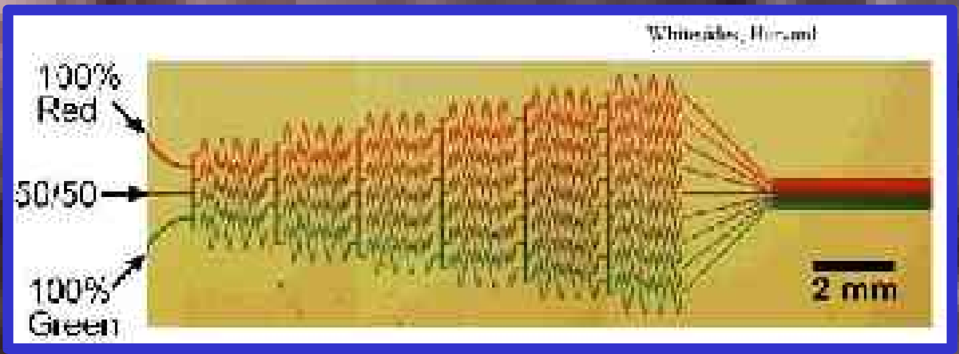
Problem: laminar flow

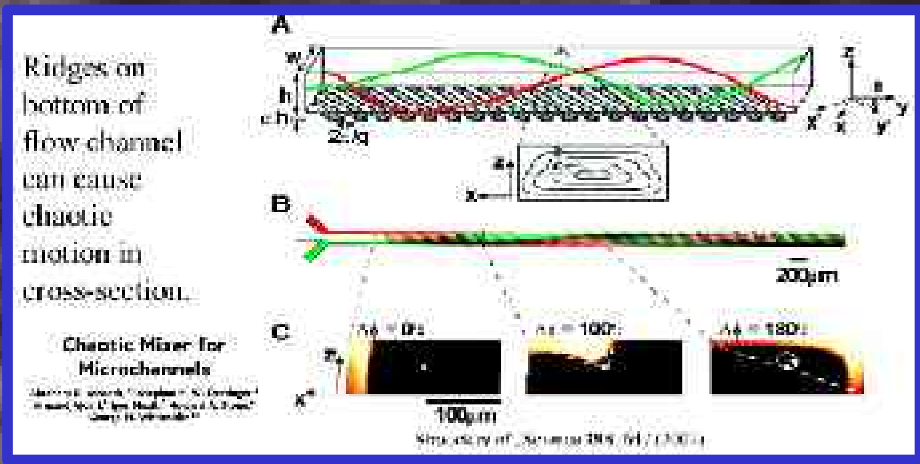


Passive Solution: bends and turns

Active Solution: induce chaos via pumping, movement

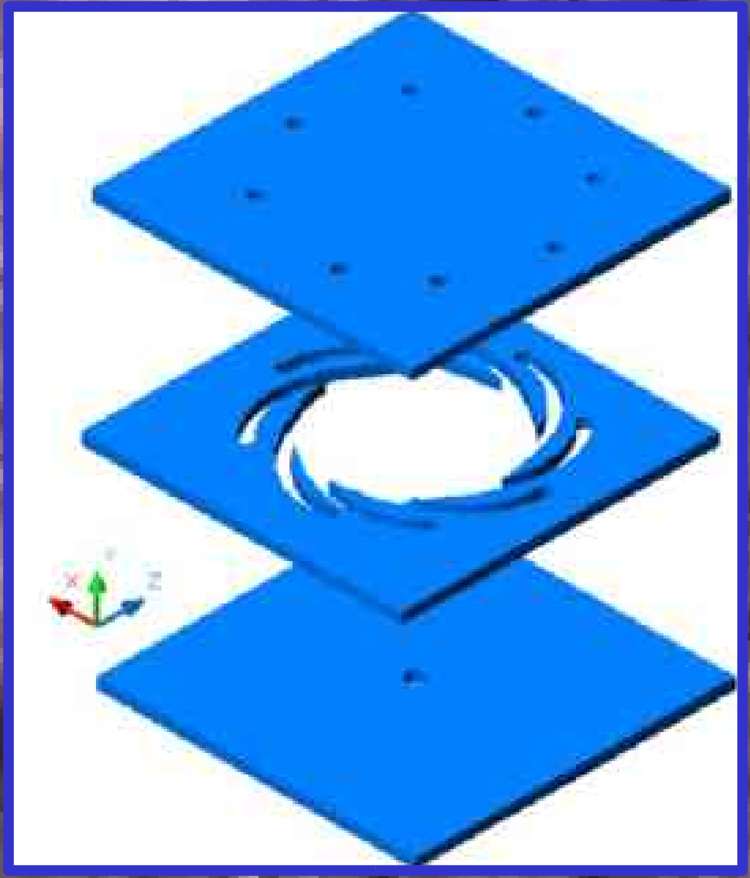
Others Mixing Schemes



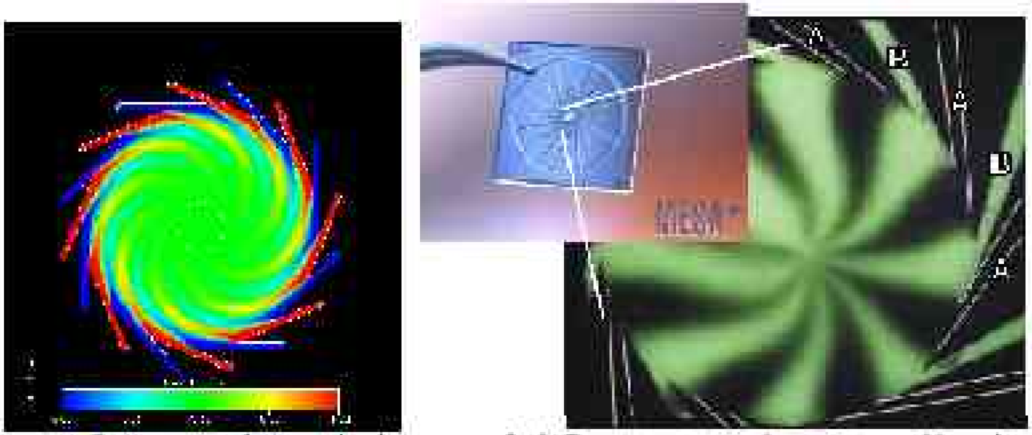


Vortex Mixer

LTCC Layer



Streamline Simulation



Cross-section of vortex chamber showing mixing process (concentration in a.u., green indicates complete mixing)

Back: First measurements showing mixing of dye at low velocity (video capture). Inset: Photo of realized device (note the circular feed-ring for liquid A, liquid B is fed from the back)

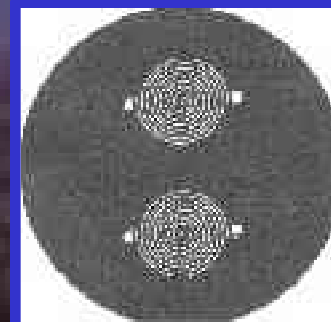
A Rapid Vortex Micromixer for Studying High-Speed Chemical Reactions

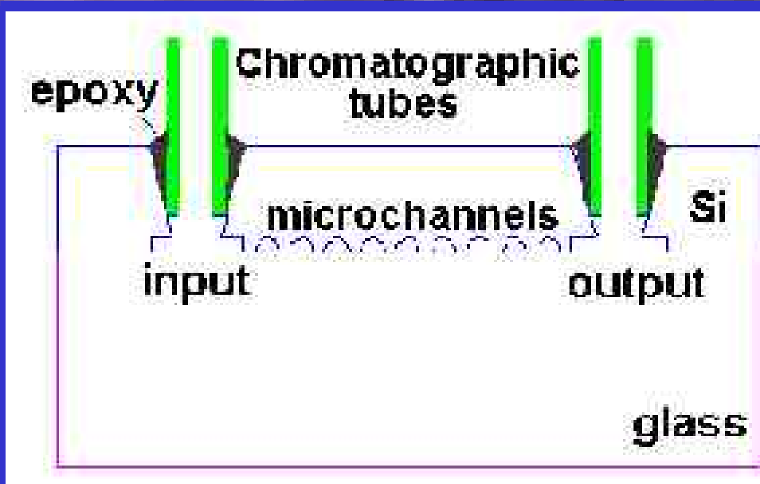
S. Böhm[1], K. Greiner[2], S. Schlautmann[1], S. de Vries[2] and A. van den Berg[1]

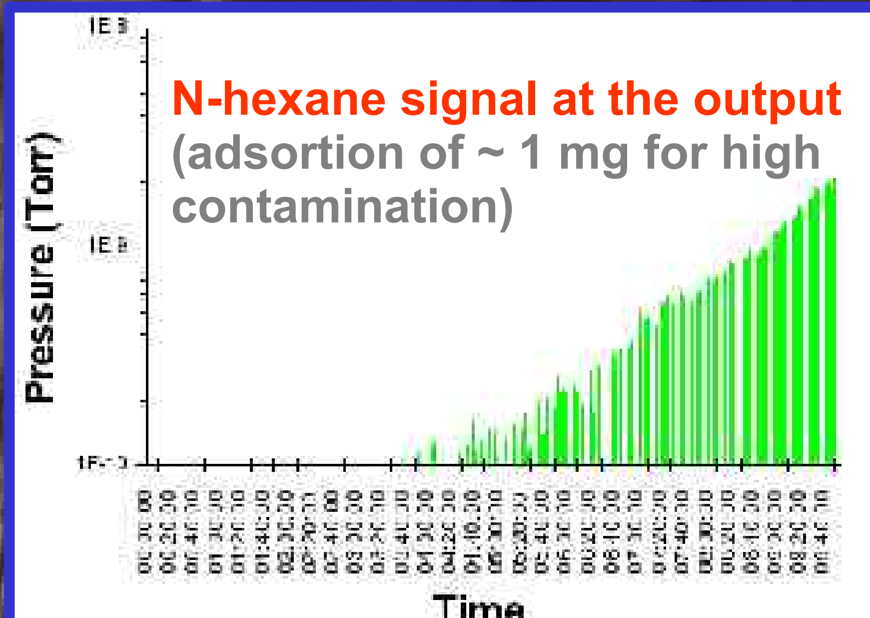
Gas contamination pre-concentrators

Use of microchannels (silicon and modified) to concentrate pollutants (hydrocarbons present in the air)

- Easily portable
- Low cost batch fabrication
- Mobile detection system





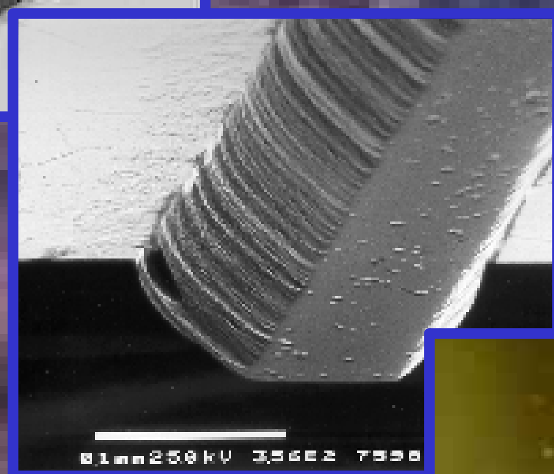


Microchannel Technology

100 µm wide x 40 µm deep x 30 cm long

Area: 3cm x 3 cm

1. Ports open with KOH or TMAH etching

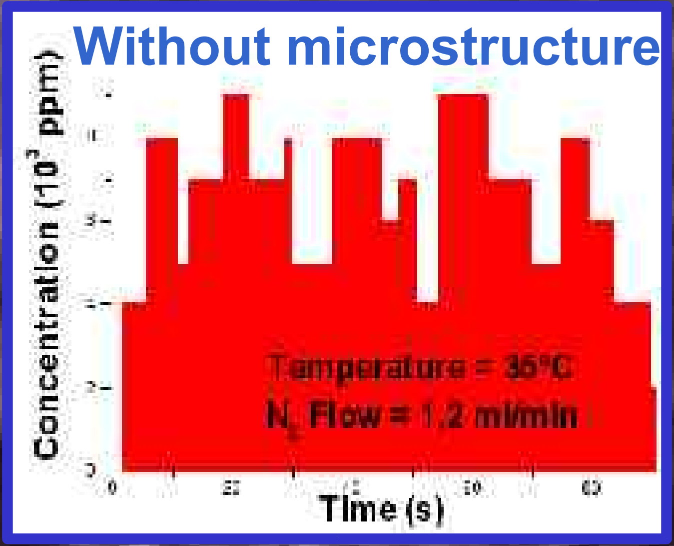


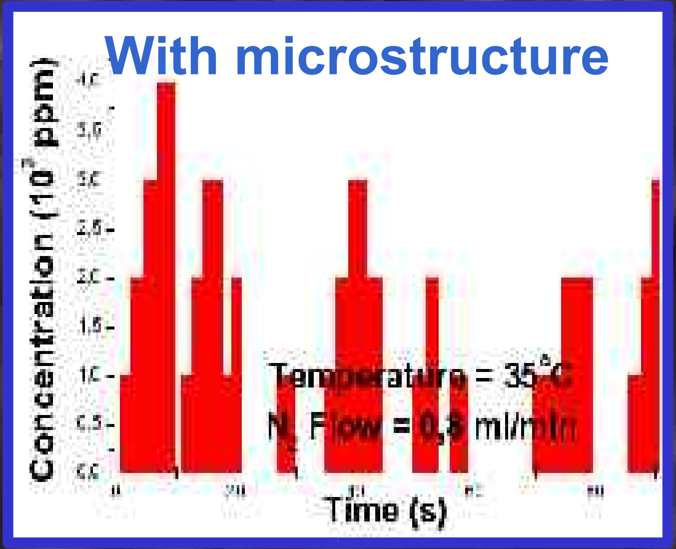
2. Microchannel isotropic etching RIE SF_6 based

3. Holes drilled in the glass before anodic bonding

4. Porous silicon formation inside the microchannels

N_2 + 1000 ppm n-hexane

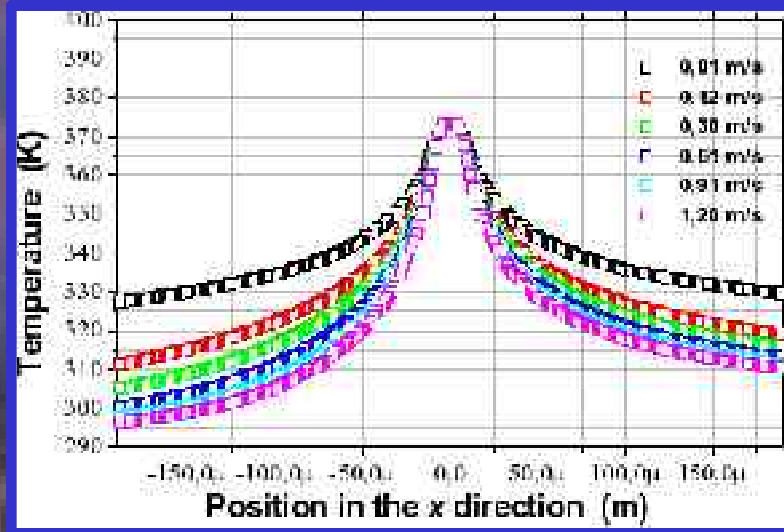


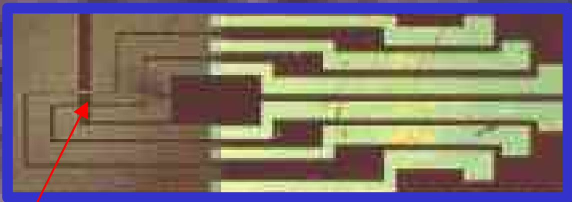


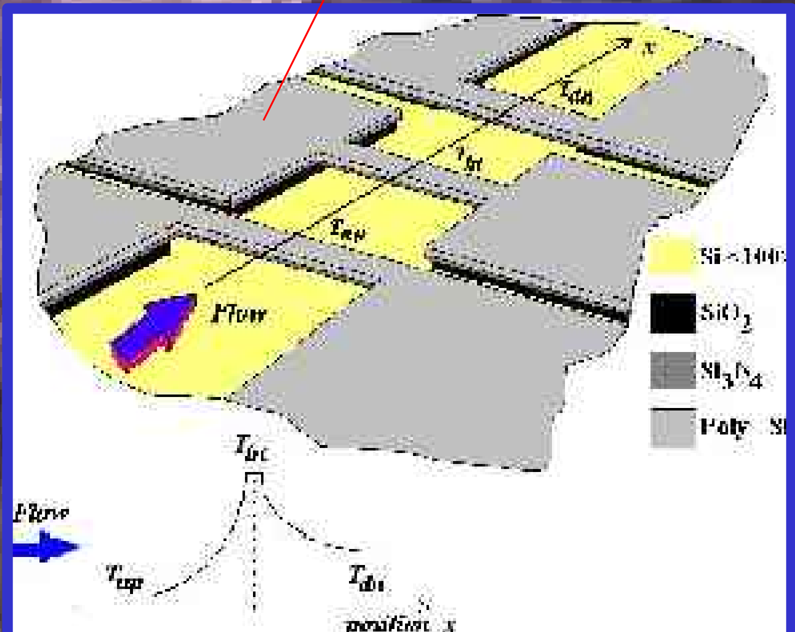
With microstructure nitrogen flow is observed at the output but n-hexane is not detected before 50 min.

Flow and gas microsensors

- **Small flow measurement, gas and liquid applications, possibility of integration in microchannels**

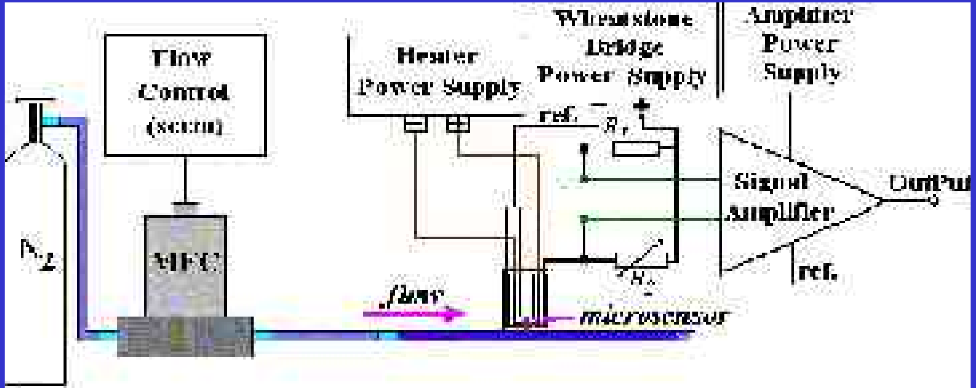


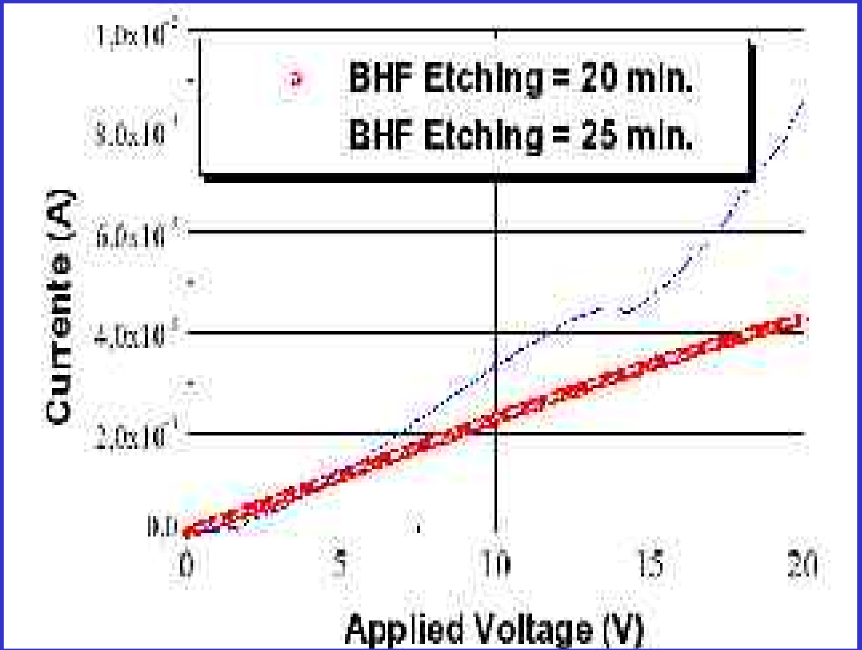


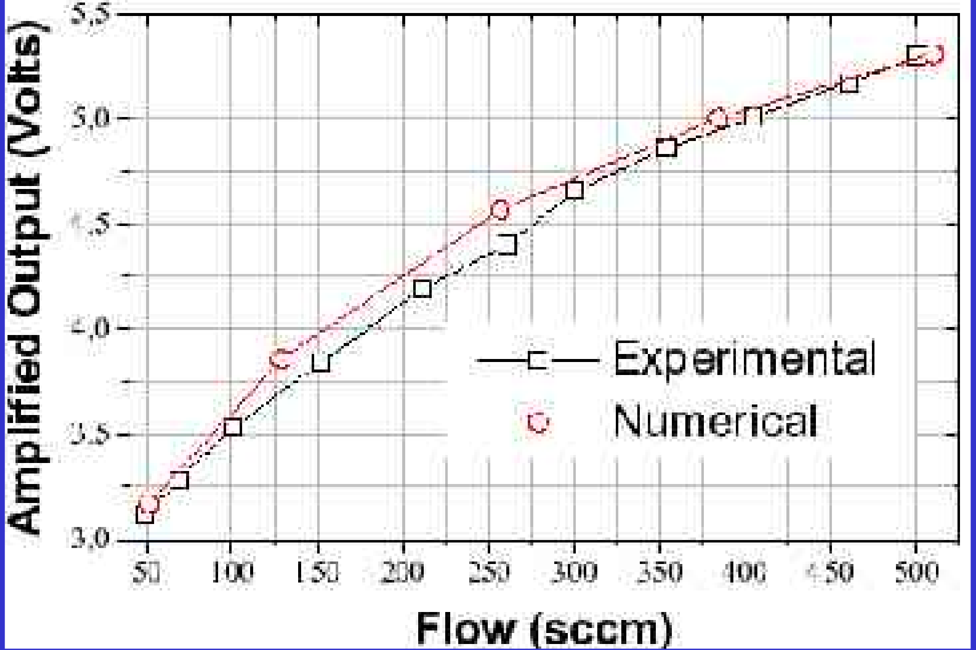


Tests with gas (N_2)

Red light emission ↙ T ~ 1100 °C







Logic Fluidic or Fluerics

Although the knowledge of fluidic principles is fairly old, it was not until about 1960 that fluidic devices, which are characterized by the absence of moving parts, started to be used commercially.

Examples:

fluidic valve　　fluidic nozzle

fluidic sensor　　fluidic interface

fluidic amplifier　　fluidic oscillator

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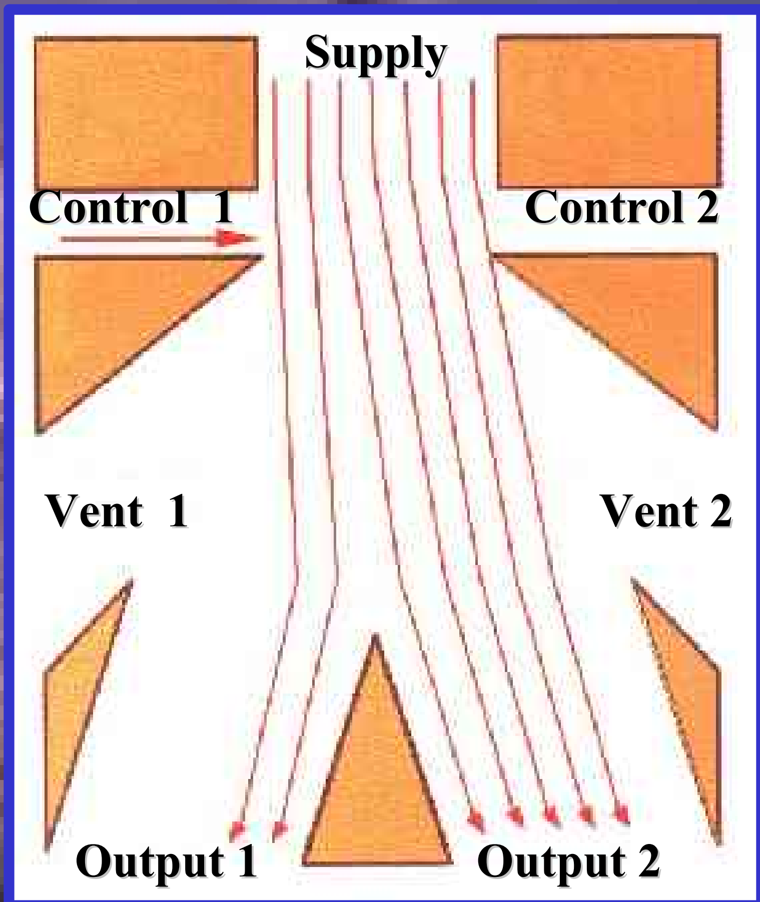
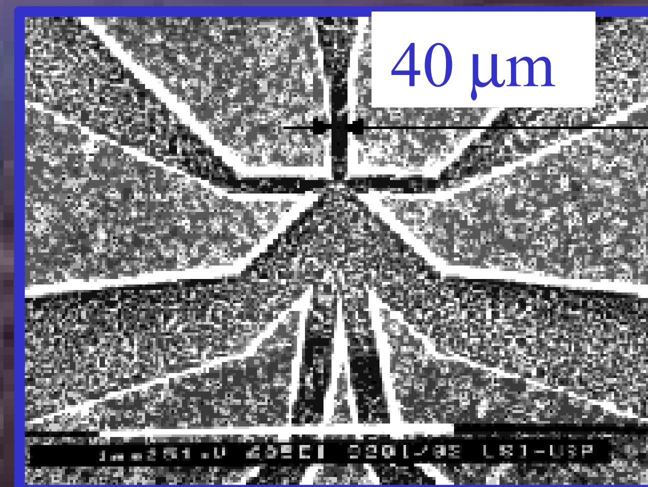
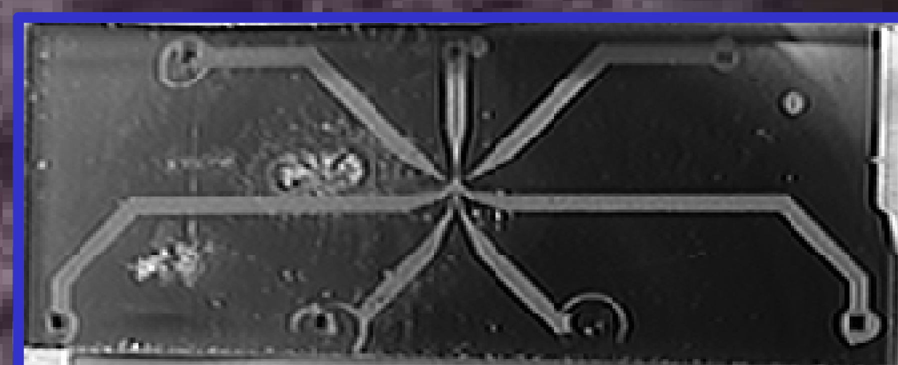
Jet Deflection Fluidic Amplifier



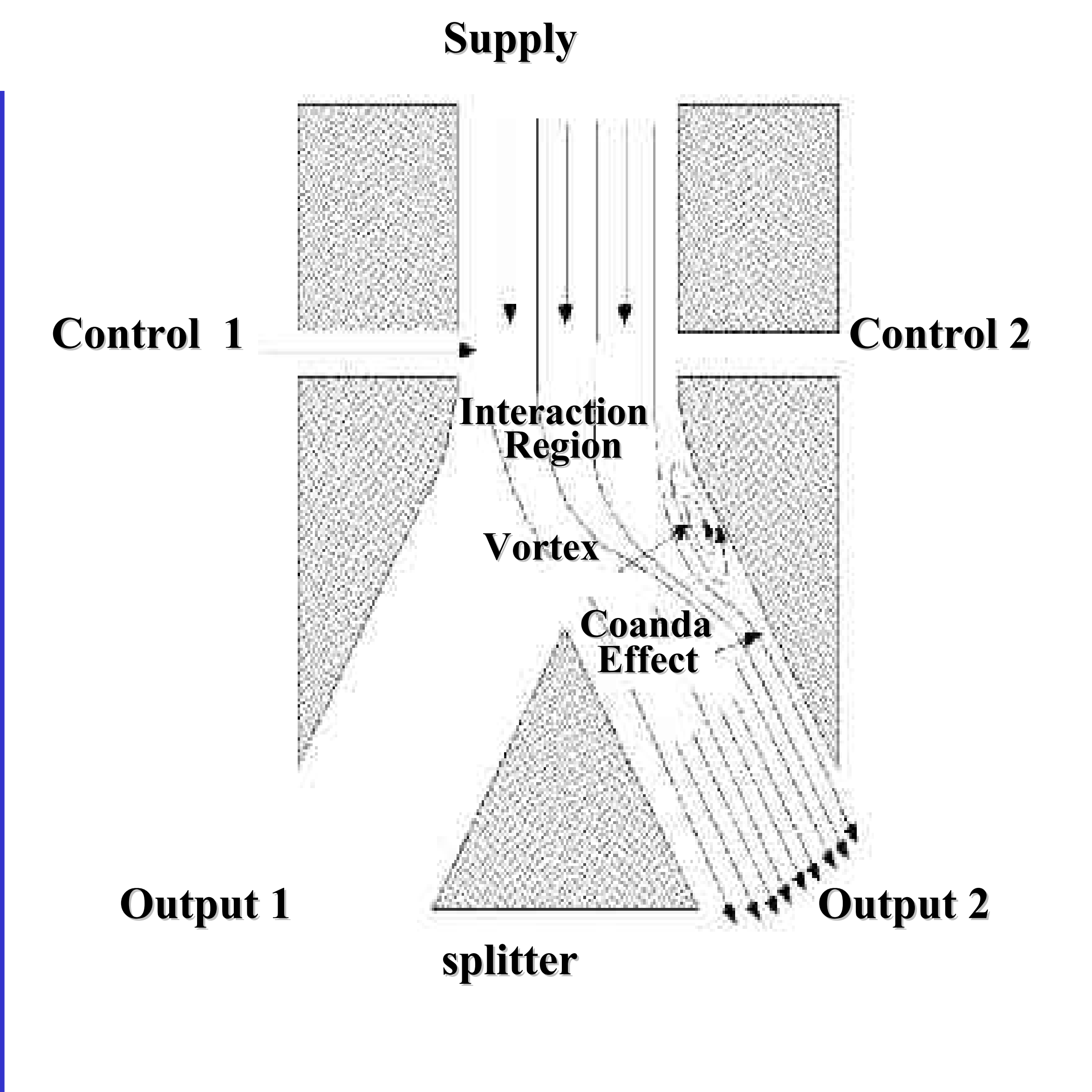
Vents (Wastes) in the interaction region



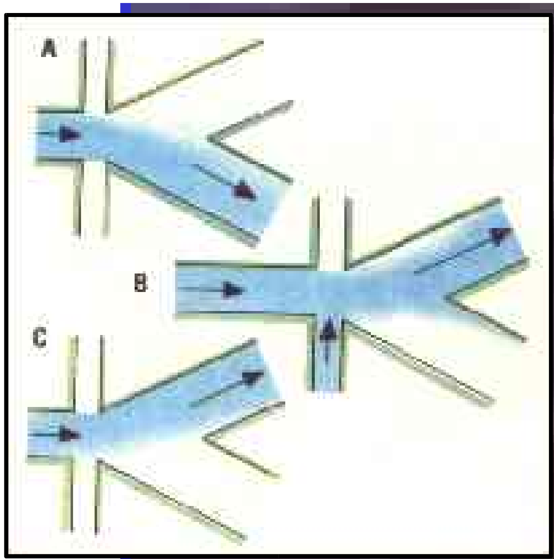


Analogic or proportional

Bistable wall attachment fluidic amplifier



bistable or digital



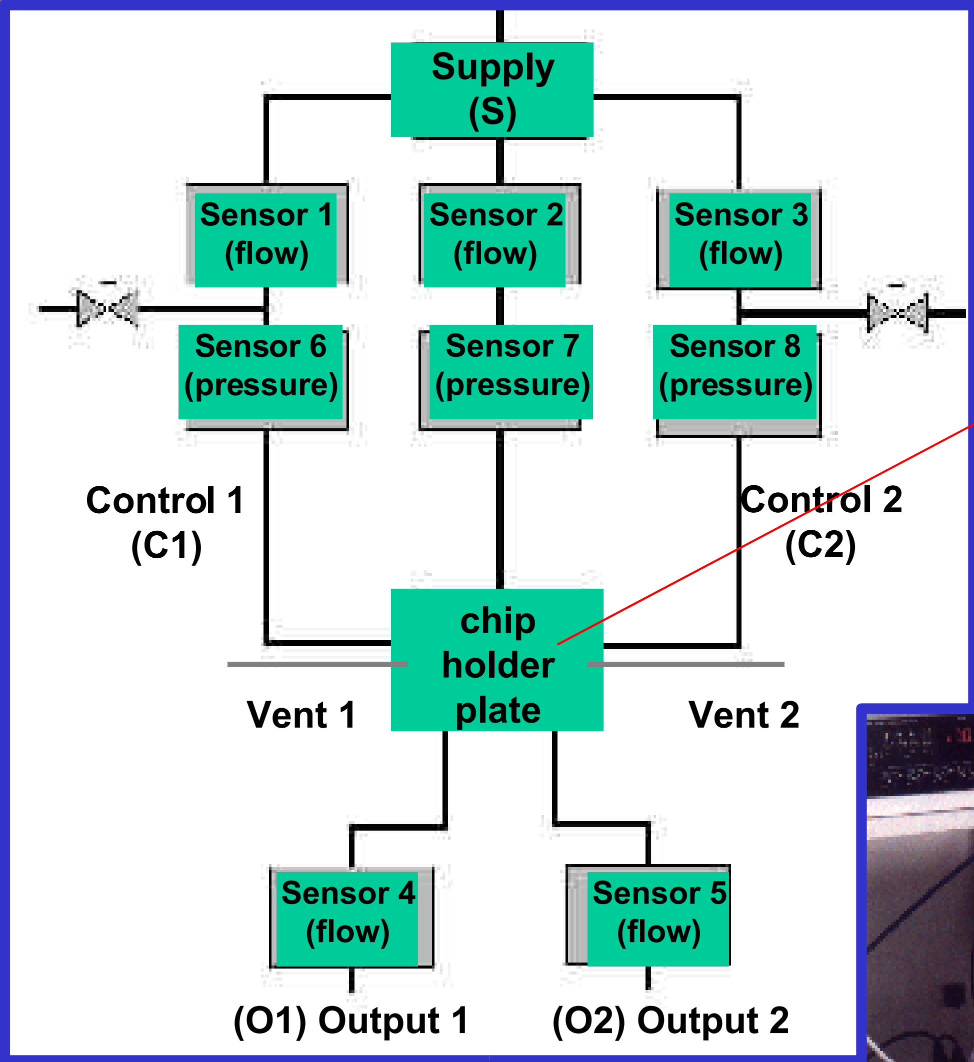
Microchannel Technology

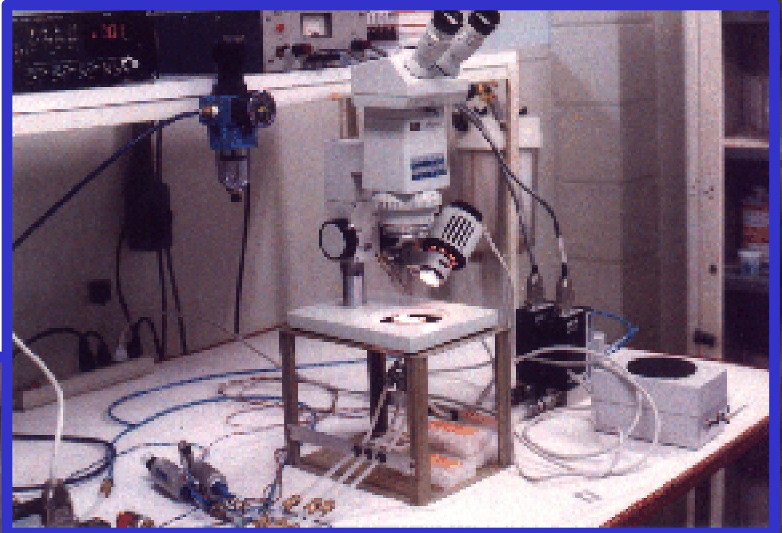
- **Silicon wet etching** - KOH - 27,4 % in water

- **Plasma etching** - HDP plasma SF_6 based - hidraulic diameters of ~ 40 μm

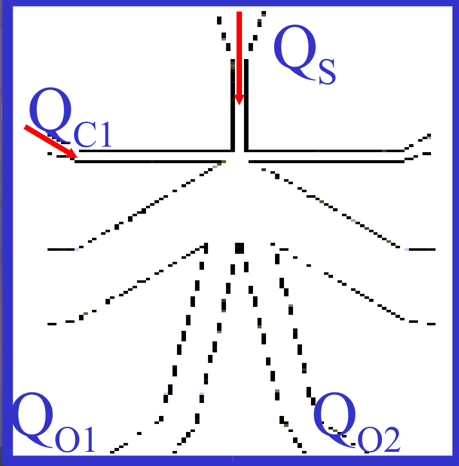
- **Anodic bonding** - 377°C/ 800 V

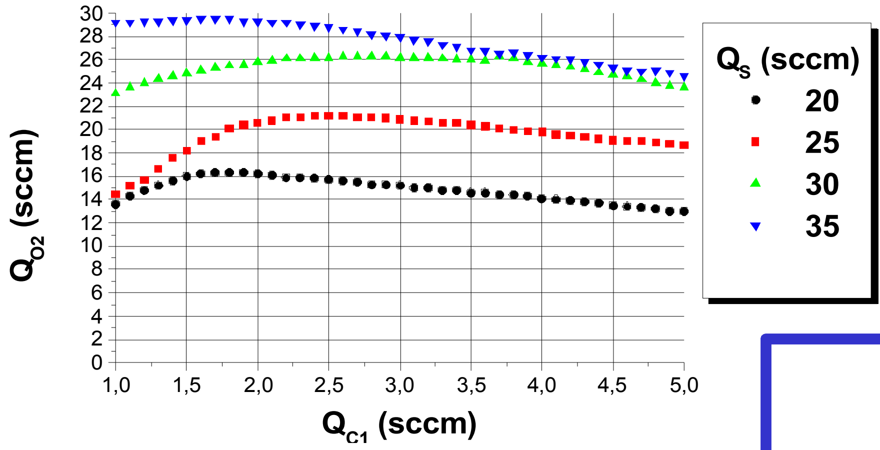
Tests with gas (N_2)

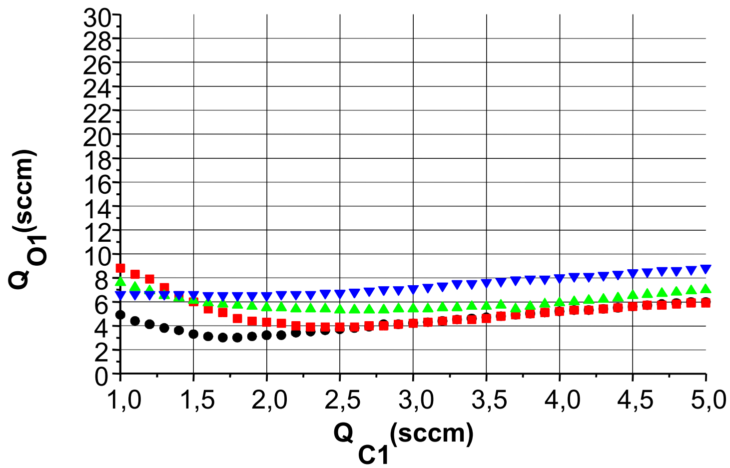


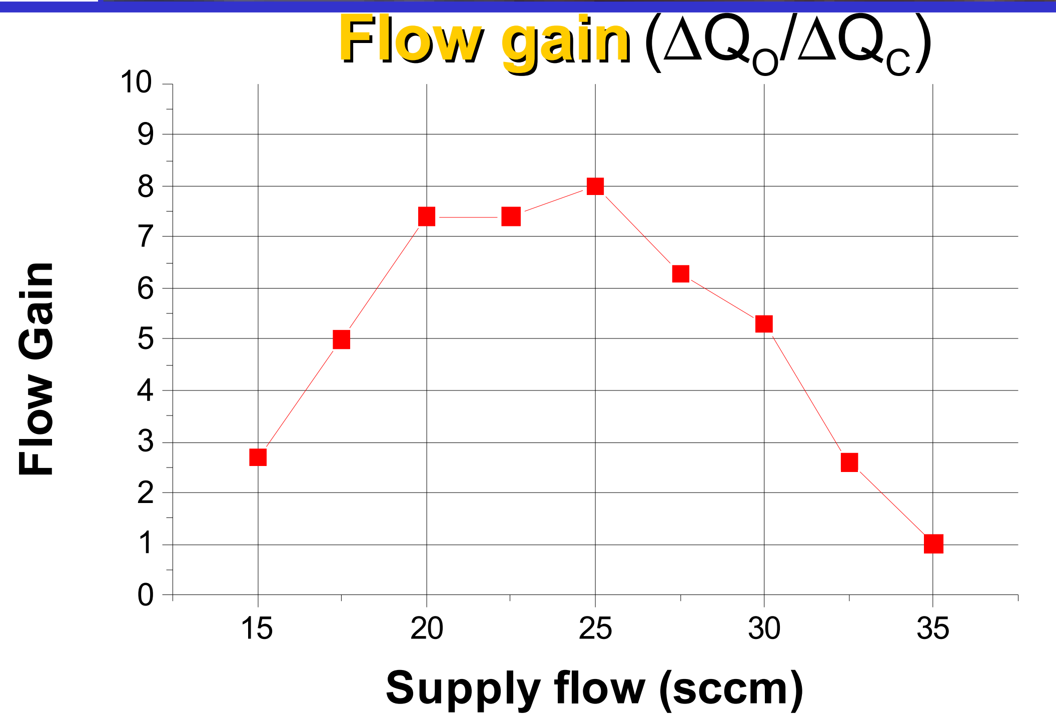


Flow control results







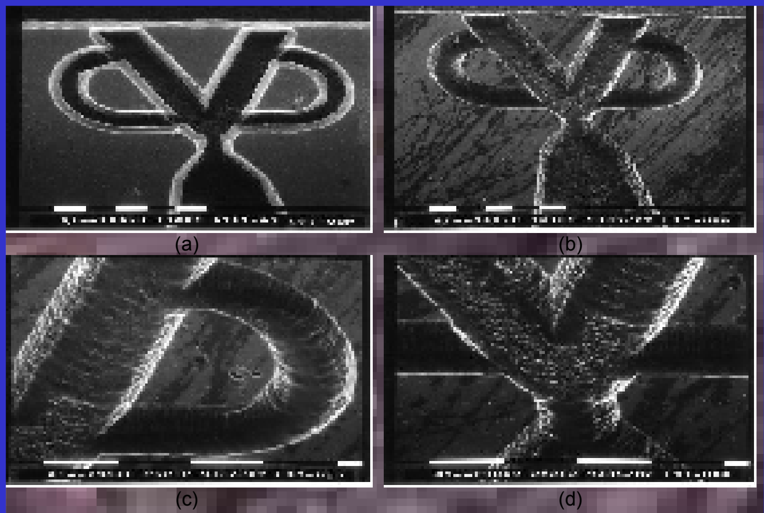


- Symmetrical behavior
- Non-zero output
- High flow gain: up to 8

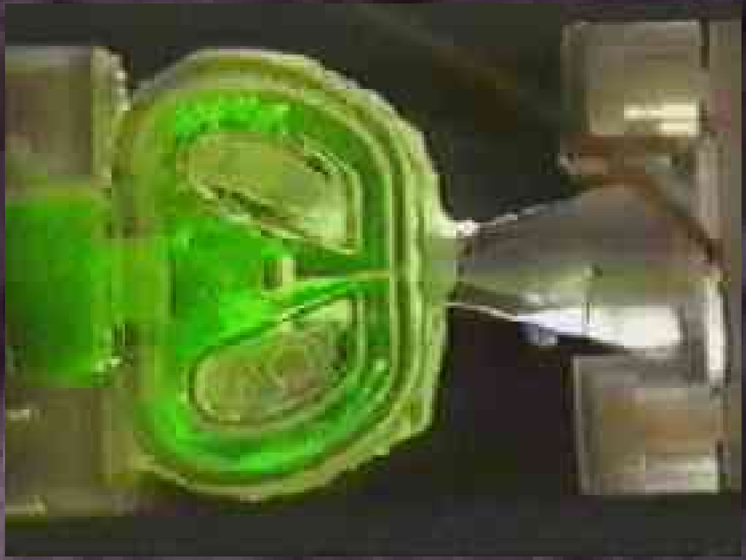
Feedback fluidic oscillator configuration

fluidic amplifier

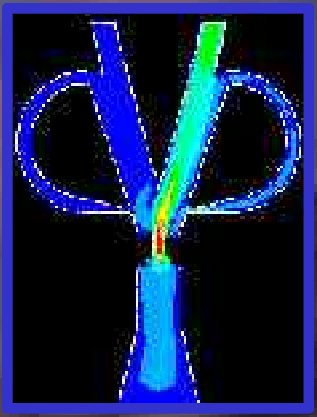
Feedback fluidic oscillator



Silicon HDP



Period of oscillation (T)



$$T = 2(\tau_t + \tau_s) = 2\left(\frac{l}{c} + \frac{\xi L}{u}\right)$$

T_t - transmission time

T_s - switching time

l - length of one loop

c - speed of wave propagation

L - nozzle-to-splitter distance

u - jet velocity

ξ - empirical constant

(for liquids)

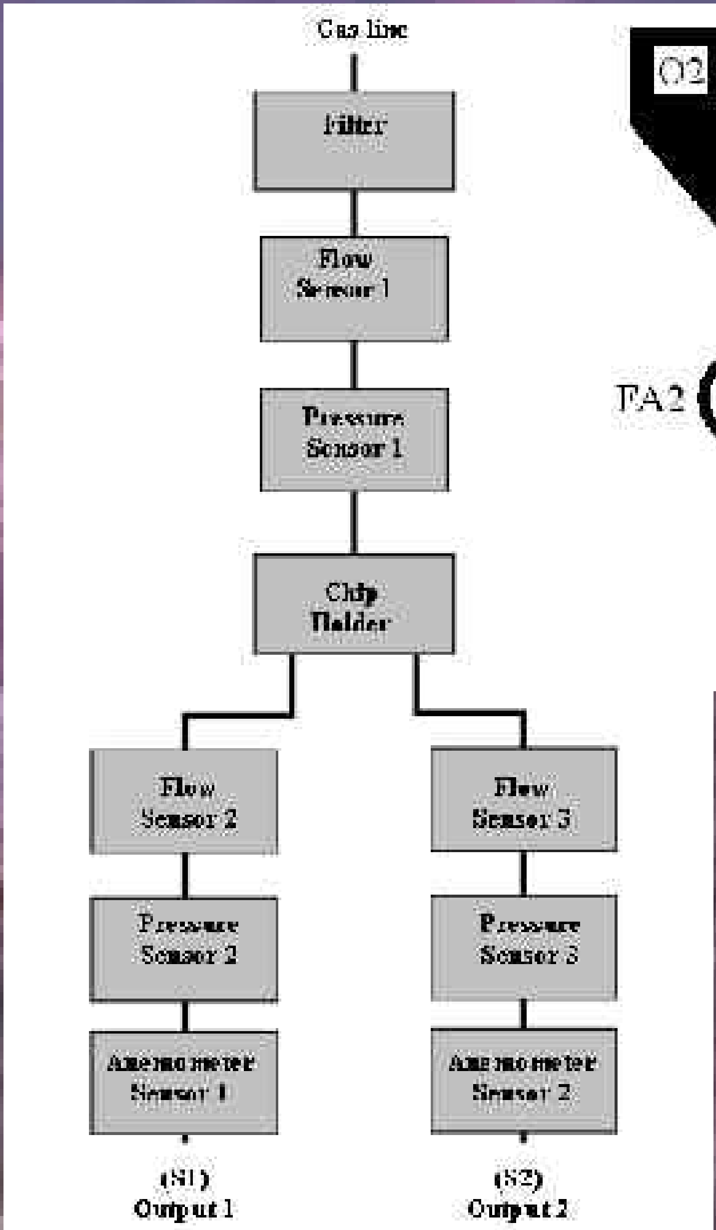
$$f = \frac{1}{2\tau_S} = a + \mathrm{b}Q$$

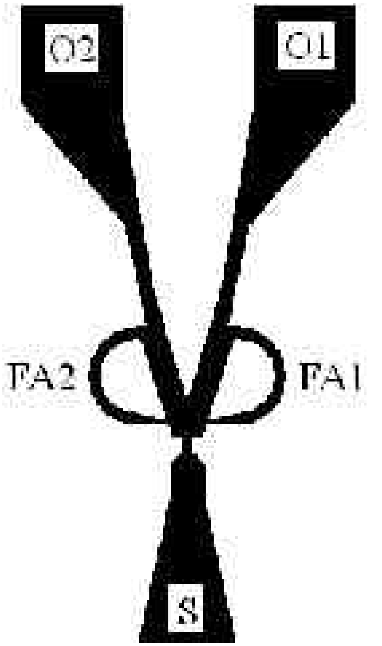
(for gases)

$$f = \frac{1}{2(\tau_t + \tau_s)} = a + \mathrm{b}Q$$

where a and b are constants and Q is the volume flow

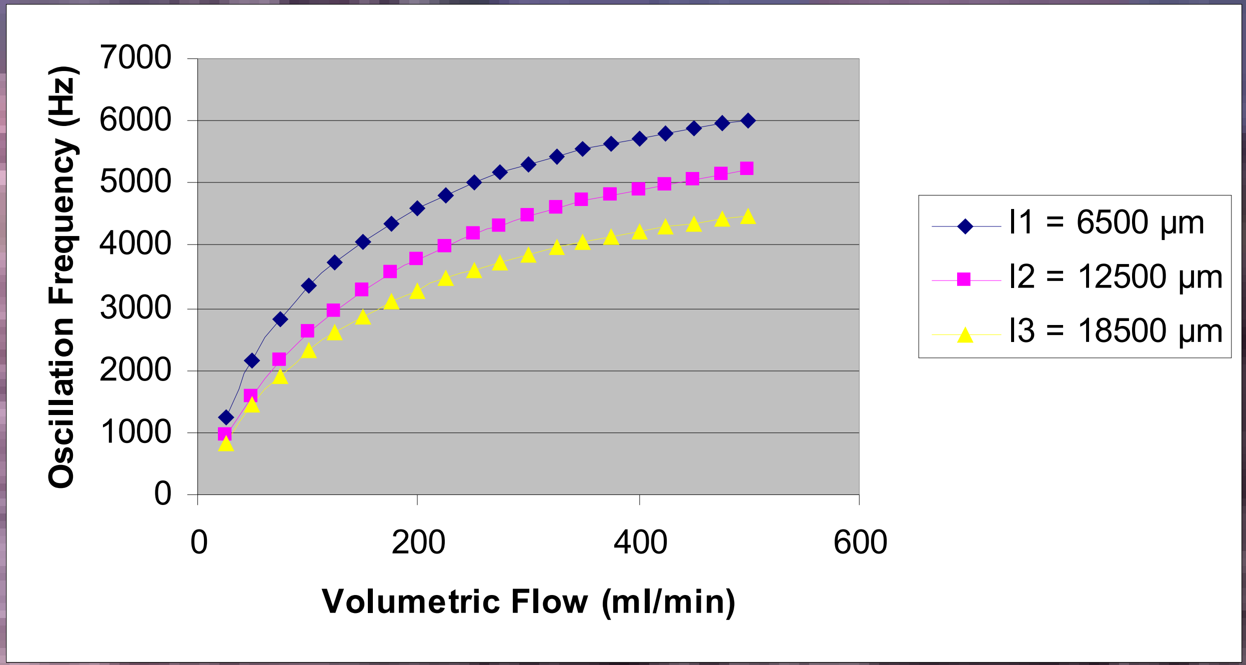
Tests with gas (N_2)

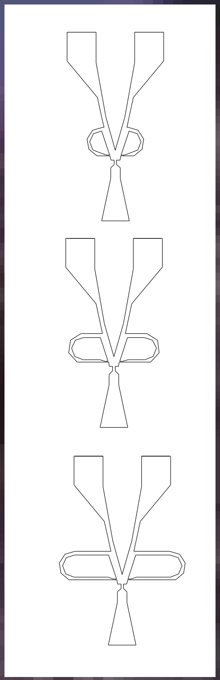




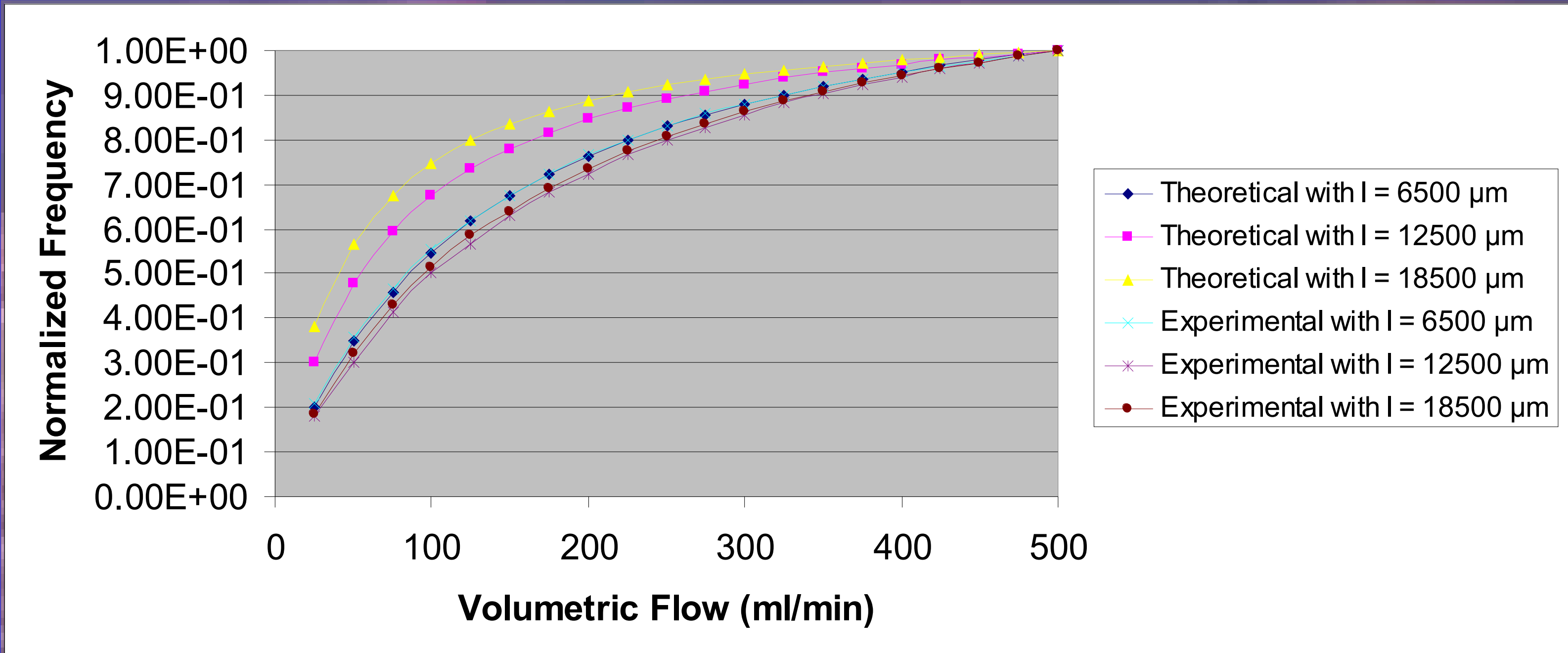
Hot Wire

12 μm





Experimental results of oscillation frequency as a function of nitrogen volumetric flow and feedback arm length (l) for a device with microchannels 100 µm deep.

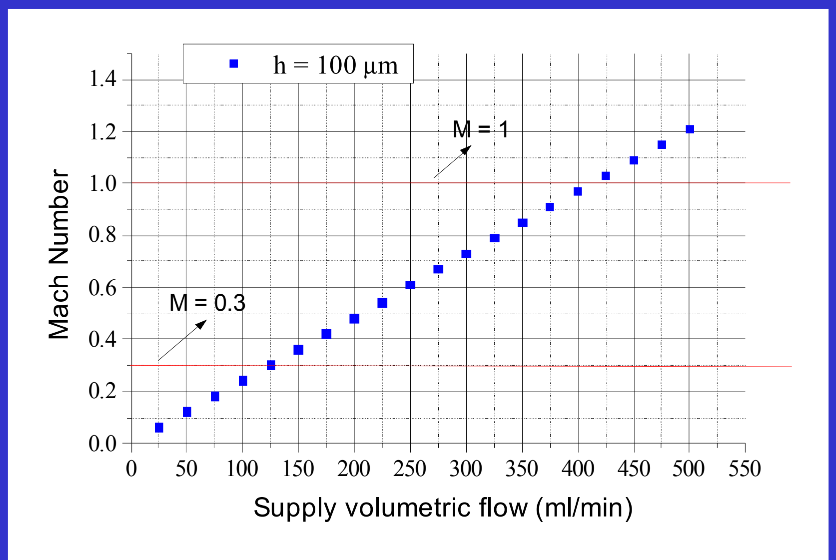


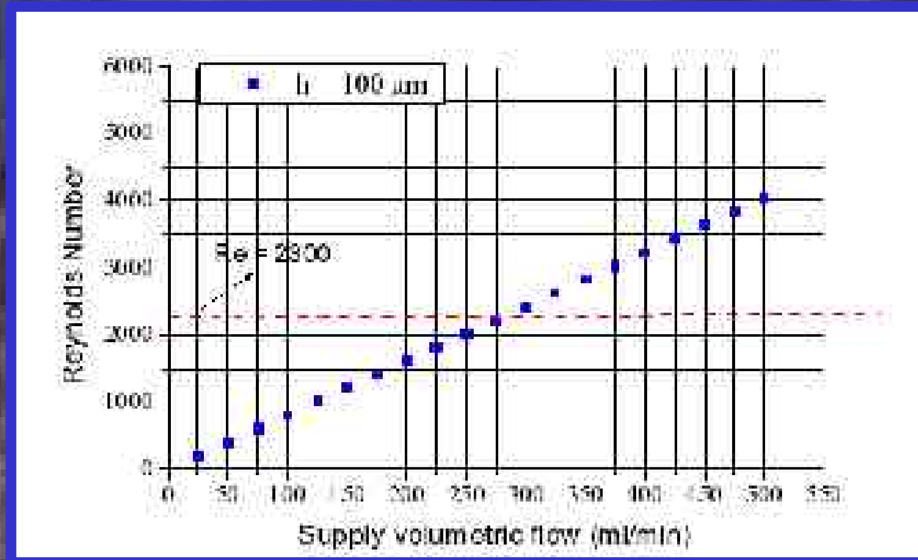
Comparison of experimental curves with theoreticalEach curve was normalized with respect to its maximum frequency (obtained for a volumetric flow of 500 ml/min).

2.8 kHz - 75 ml/min

3.7 kHz - 125 ml/min

5.4 kHz - 325 ml/min

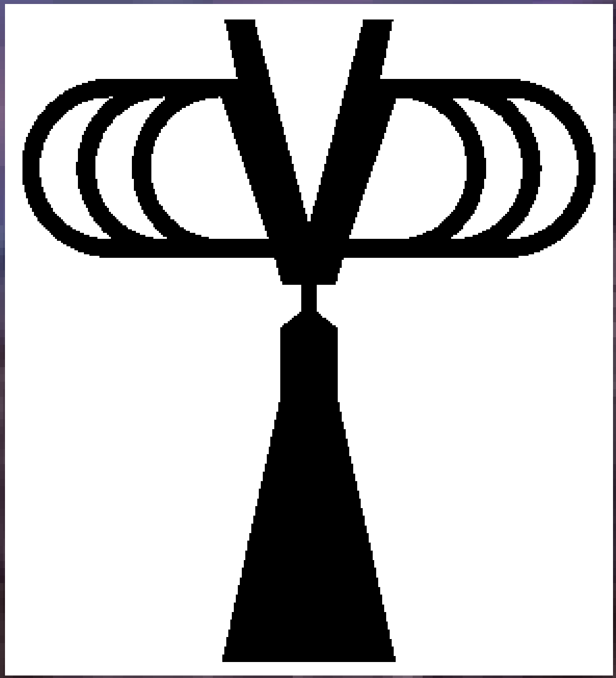




Mach Number and Reynolds Number estimated at the output of the supply nozzle.

Microfluidic oscillator possible applications

- **Flow Measurement**
- **Material handling**
- **Medical, biological, and chemical analysis**
- **Aerospace and military**
- **Several others areas**



Microfluidic Mixer

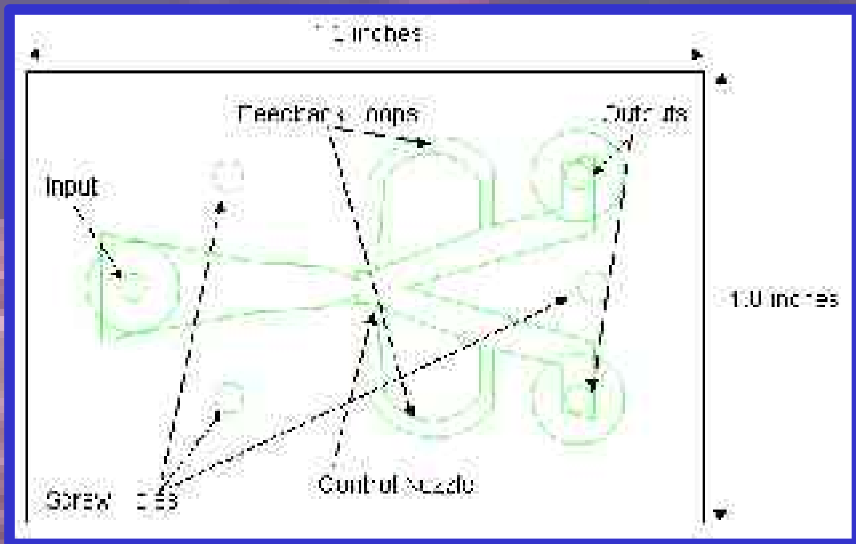
Fluidic flowmeters

- **Elimination of electrical contacts prevents a possible fire hazard in several cases**

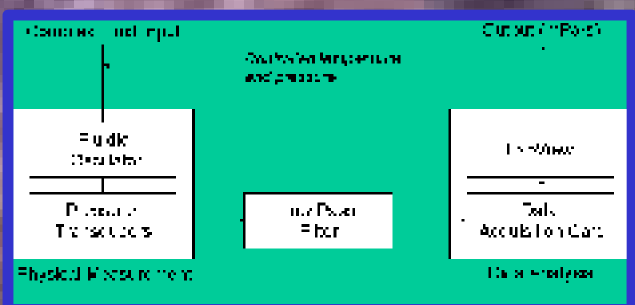
Viscosity measurement

Measuring viscosity has become vitally important to the silicon wafer industry. To achieve the desired high level of accuracy, viscometers have become increasingly expensive and complex.

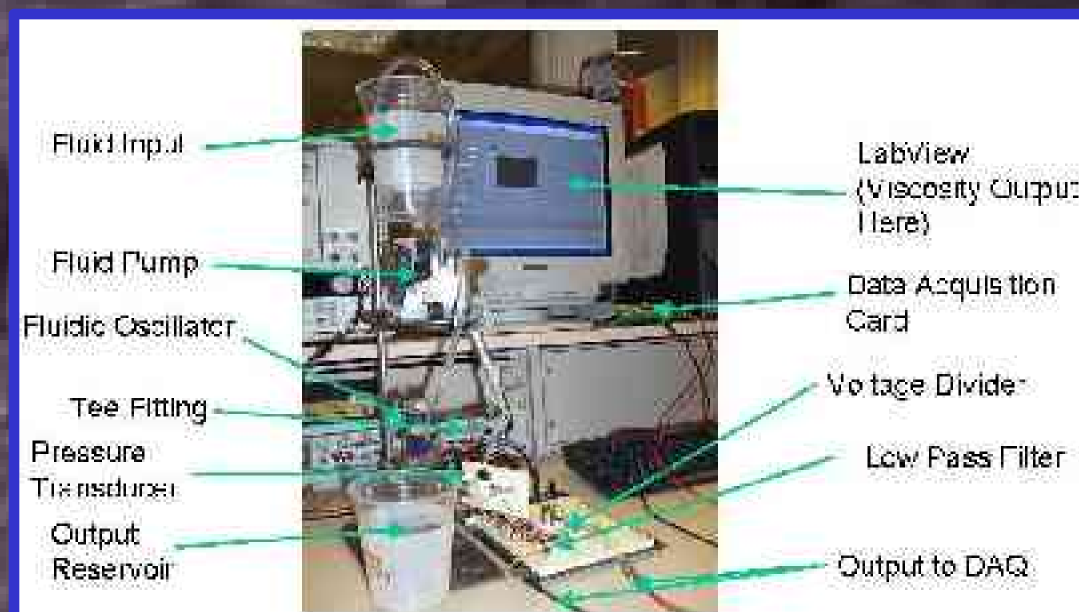
- Relatively inexpensive
- Capable of evaluating slurries and other complex fluids based on the concept of fluidic oscillation
- Accurate to ±5 percent over a measuring range of 10^0-10^5 mPa•s using a sample volume less than 20mL
- Easy to use
- Capable of measuring viscosity quickly

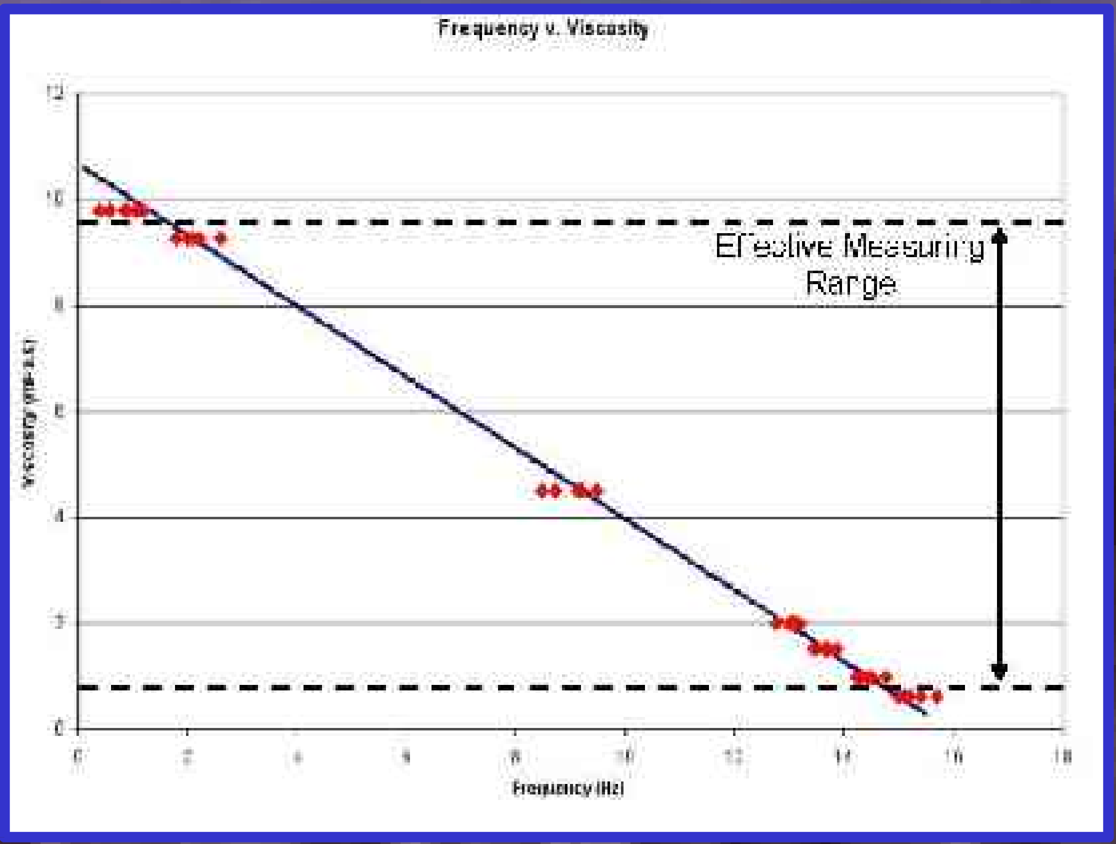


Device configuration



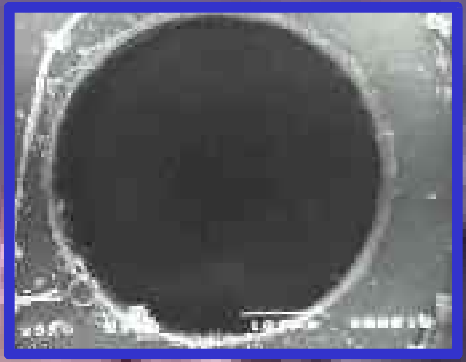
System Block Diagram for Fluidic Oscillation Viscometer





Relationship between frequency of oscillation and viscosity . Methyl alcohol and three solutions of milk thickened with varying quantities of starch were used to test the ends of the range

Micro orifices



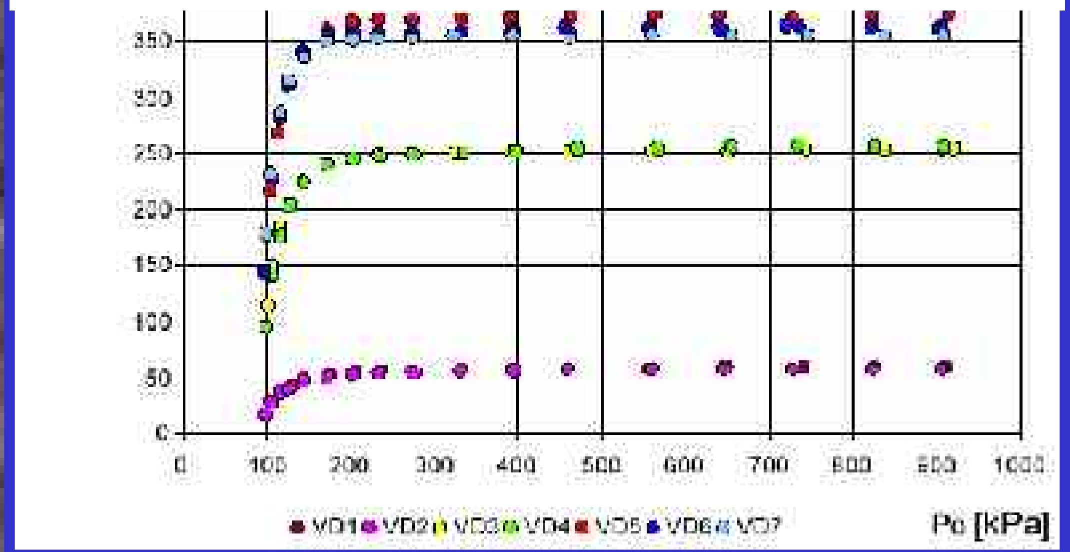
Stainless steel

Green Ceramic

Ruby

Different orifice diameters (90, 180, 210 µm)

Volumetric Flow x Input Pressure

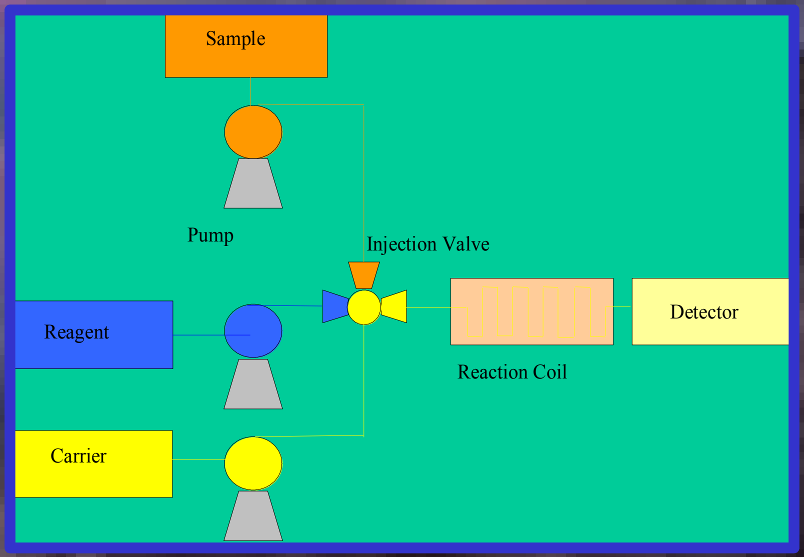


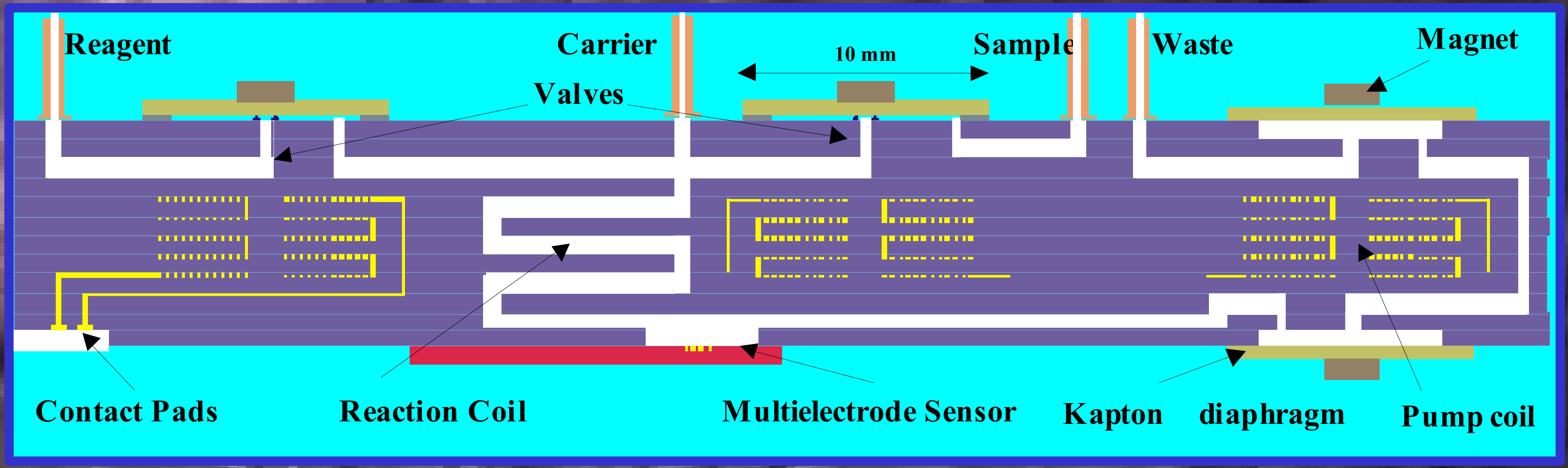
Basic FIA Scheme

FIA - Flow Injection Analysis

FIA miniaturization is interesting due to several advantages:

- Sensor can have its sensibility and selectivity optimized;
- Time for analysis is 10 to 100 s, allowing up to 300 analysis/hour;
- System performance is enhanced.

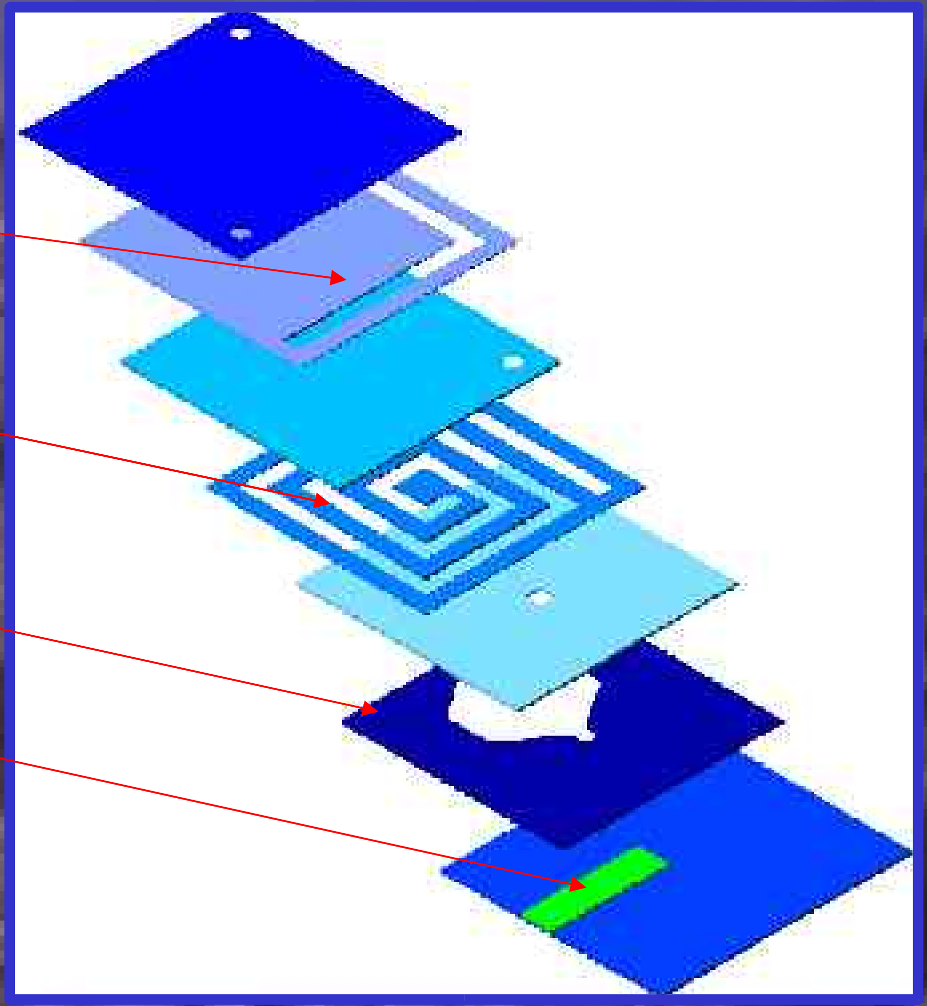




FIA Manifold

Manifold Layers

- Input Layer
- Merging Layer
- Fluid Via
- Spiral Mixer
- Fluid Via
- Sensing Cavity
- Sensor
- Base



Conclusions

- Very promising field of applications
- Easy operation
- Precise analysis
- Effective to be used as pre -concentrators
- Gas and liquid flow control, actuation, and measurement
- LTCC possibility of fabricating three-dimensional structures using multiple layers of LTCC tapes
- Biological manipulation and diagnostics
- Chemical and Thermal sensing and analysis

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