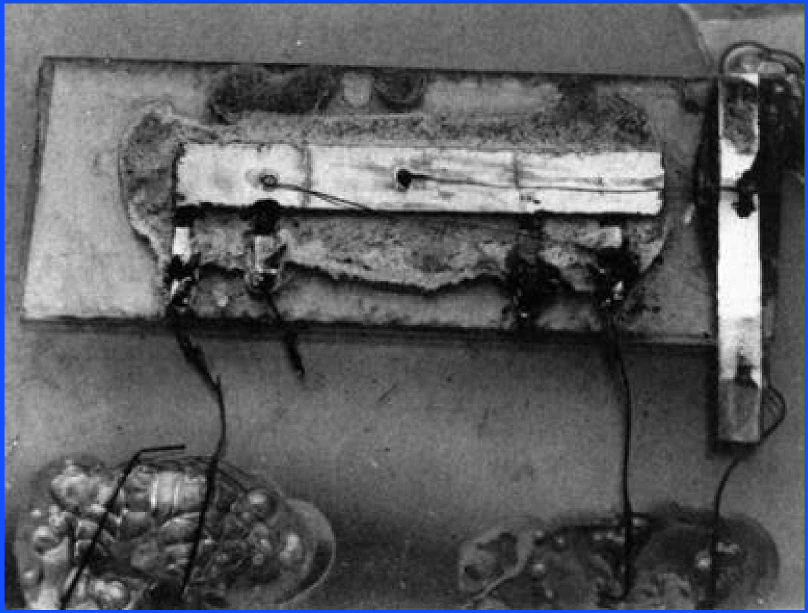
MICROFLUIDIC DEVICES

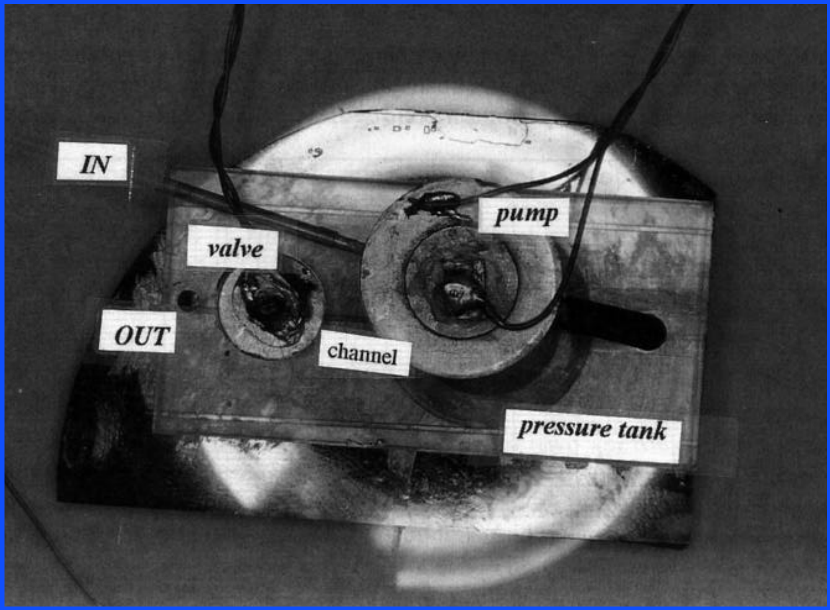
EE312, Prof. Greg Kovacs

Stanford University

STATE OF THE ART IN MICROFLUIDICS?



First integrated circuit (Jack Kilby, summer 1958).



"Micro fluid handling system" (Croce, et al, 1994).

Sources: (left) Runyan, W. R., and Bean, K. W., "Semiconductor Integrated Circuit Processing Technology," Addison-Wesley, 1990,(right) Croce, N., Carrozza, M. C., and Dario, P., "A Fluid Handling and Injection Microsystem for µTAS," Proceedings of the µTAS '94 Workshop, Twente, Netherlands, Nov. 21 - 22, 1994, pp. 195 - 198.

MICROFLUIDIC SYSTEMS

- **Pumps**
- **Valves**
- **Flow channels**
- **Flow sensors**
- **Mixers**
- **Filters**
- **Integrated microfluidic systems**

ISSUES FOR MICROFLUIDICS

Issue	Macroscopic	Micromachined
Unwanted turbulent flow?	Y	N
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)

BASIC FLUIDICS CONCEPTS

- "Fluidics" covers both gases and liquids.
- Basic properties of fluids are important: density, viscosity, chemical properties, etc.
- Bernoulli's principle relates velocity to pressure in steady-state flow in channels of varying dimension,

$$P_2 = P_1 + \frac{1}{2}\rho\left(v_1^2 - v_2^2\right)$$

- For Newtonian fluids, shear stress is linearly related to rate of movement (for the velocities encountered in microfluidics, most fluids can be treated as Newtonian.
- Typically, liquids used are incompressible.
- Flows can be laminar or turbulent.

LAMINAR OR TURBULENT FLOW?

- **For any fluid, one can define the Reynold's Number, which is the ratio of inertial force to friction force and indicates the relative potential for turbulence in a flow stream,**

$$R_e = \frac{\rho \, v \, L}{\mu}$$

- **ρ = density (kg/m^3), v= characteristic velocity in m/s, L= characteristic length in m, μ = viscosity (kg/m•s)**
- **For a given fluid, there is a critical value, R_c, above which the flow is potentially turbulent and below which it is potentially laminar.**
- **For *macroscopic* devices, $R_c \approx 2300$ (the corresponding value for microscale devices is not necessarily identical), but for microfluidics, the typical Reynolds number is far smaller (e.g. water flowing at 100 µl/min thorugh 100 X 100 µm channels has $R_e \approx 20$... *microflow is almost always laminar.***

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

Substance	Temperature (°C)	Viscosity (centiPoise = 0.01 gm/(sec•cm))
Water	0	1.787
Water	20	1.002
Water	100	0.2818
Water Vapor	100	0.01255
Blood	37	4.5 - 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

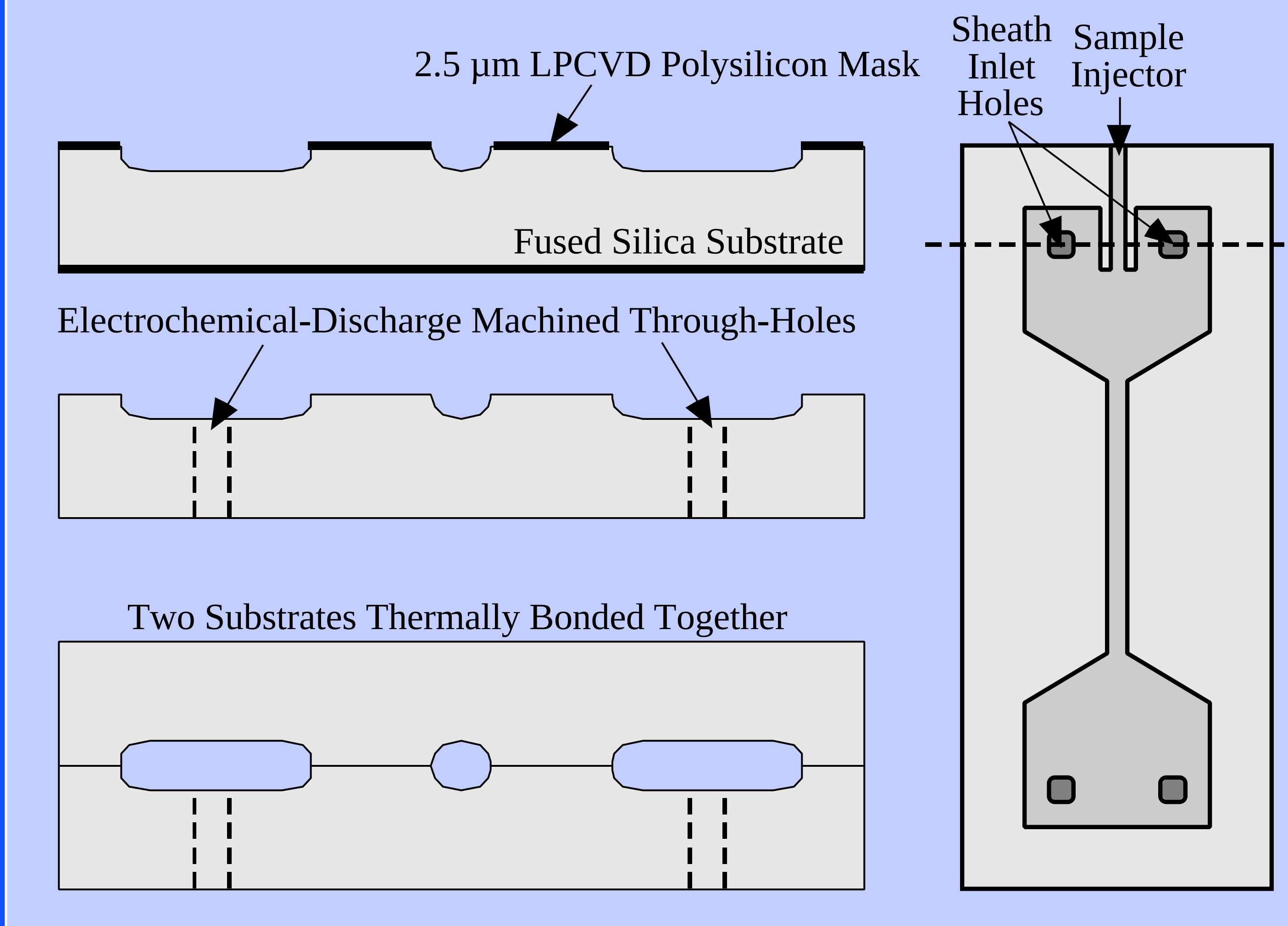
MICROFLUIDICS ISSUES

- Because laminar flow tends to reduce dead volumes and micromachined structures have very large surface-to-volume ratios, microfluidic devices can present a significant advantage over macroscopic equivalents in this respect.
- Particles in microfluidic systems are of considerable importance because they may be of comparable size to flow channels and may become lodged between control surfaces of valves, pumps, etc.
- Bubbles at the microscale may require relatively large pressures for purging.

EQUIVALENT CIRCUITS FOR FLUIDICS

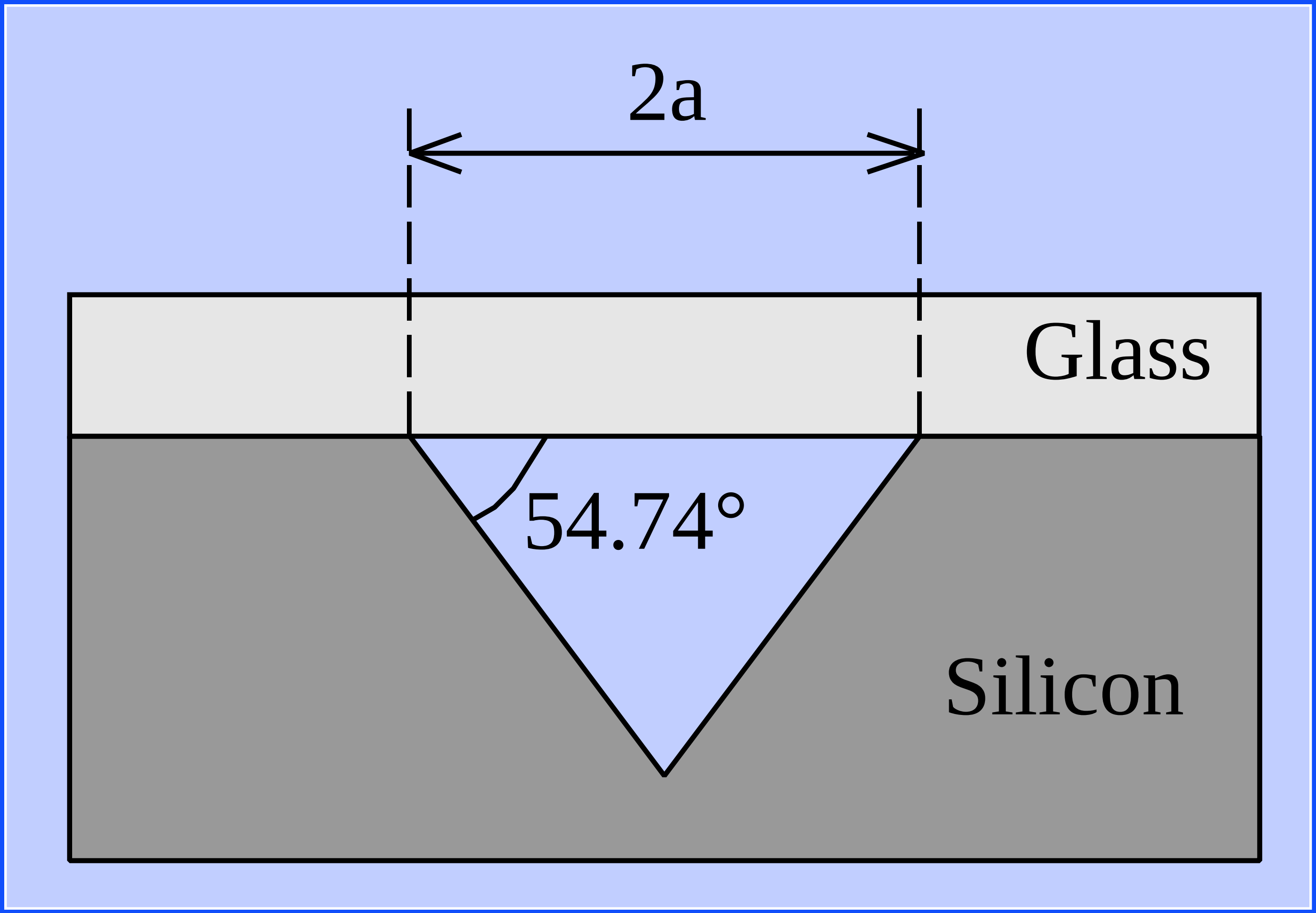
- **Fluidic circuits can readily be modeled as electrical circuits.**
- **Pressure is analogous to voltage.**
- **Flow is analogous to current.**
- **Fluidic resistance represents the difficulty a fluid has flowing in a channel or structure at a given pressure.**
- **Fluidic capacitance represents energy storage either in compressability of the fluid or compliance of the structures.**
- **Fluidic inductance represents energy storage in the momentum of the fluid.**
- ***For micromachined fluidic systems, the channels are typically rigid and, if liquids are used, they are incompressible, so fluidic resistance and inductance tend to dominate.***

FLOW CHANNELS IN GLASS



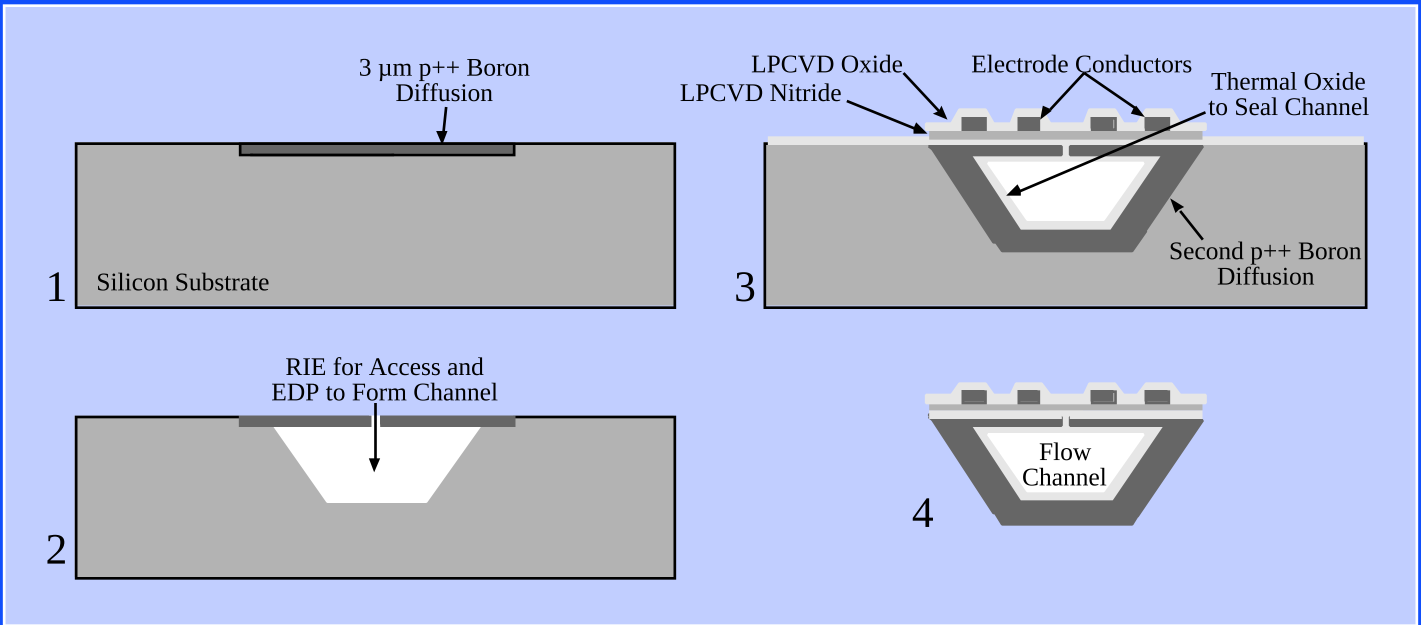
Reference: Sobek, D., Senturia, S. D., and Gray, M. L., "Microfabricated Fused Silica Flow Chambers for Flow Cytometry," Proceedings of the Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 260 - 263.

FLOW CHANNELS IN SILICON



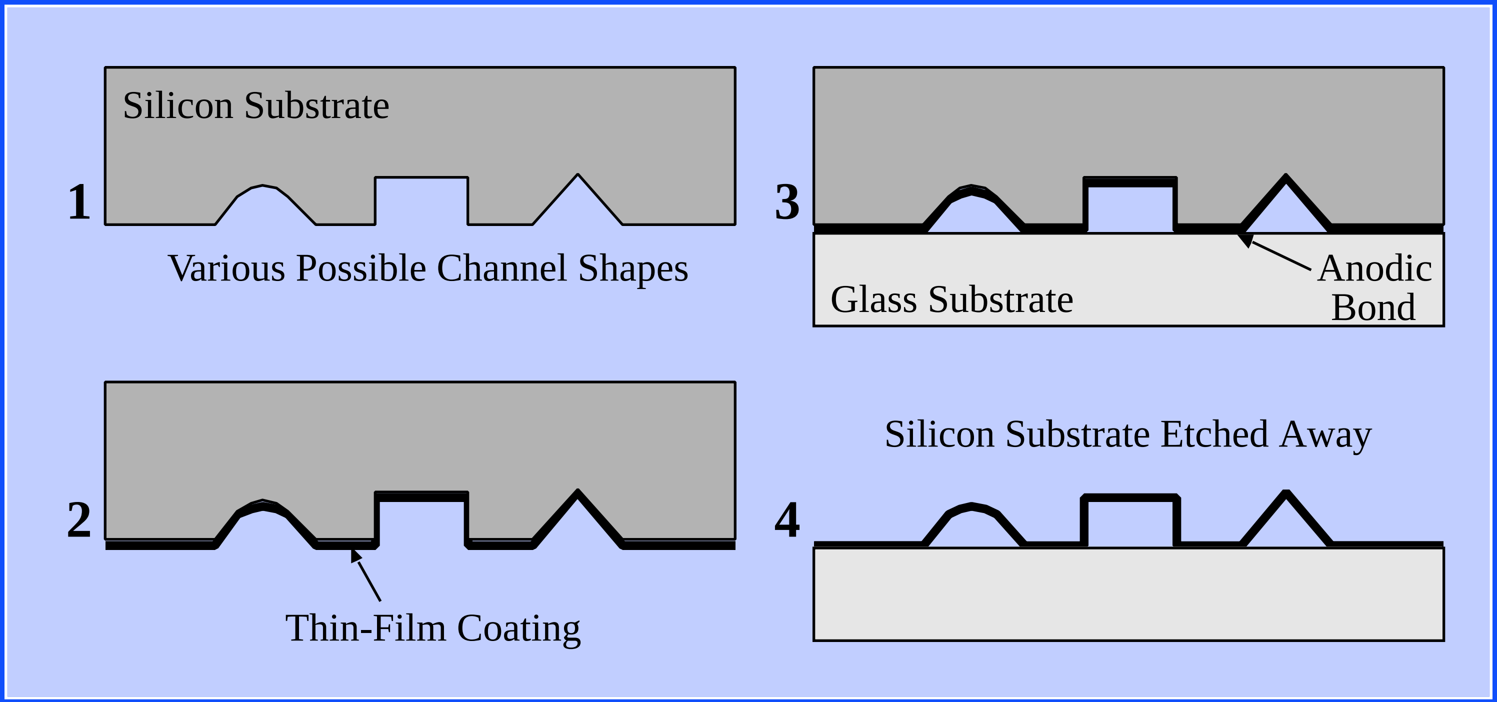
Reference: Lammerink, T. S. J., Speiring, V. L., Elwenspoek, M., Fluitman, J. H. J., and van den Berg, A., "Modular Concept for Fluid Handling Systems - A Demonstrator Micro Analysis System," Proceedings of the 9th Annual Workshop on Micro Electro Mechanical Systems (MEMS '96), San Diego, CA, Feb. 11 - 15, 1996, pp. 389 - 394.

FLOW CHANNELS IN SILICON



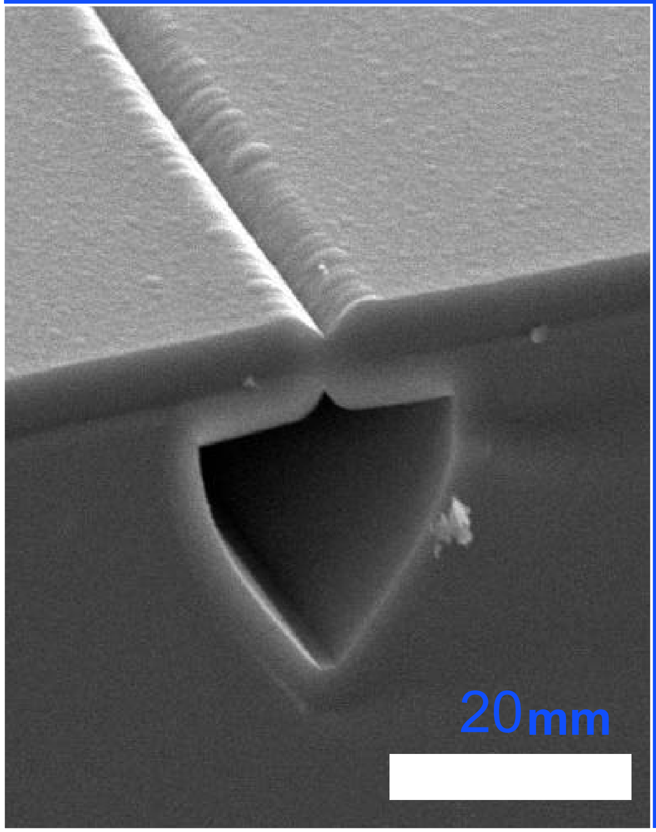
Reference: Chen, J., and Wise, K. D., "A Multichannel Neural Probe for Selective Chemical Delivery at the Cellular Level," Proceedings of the Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 256 - 259.

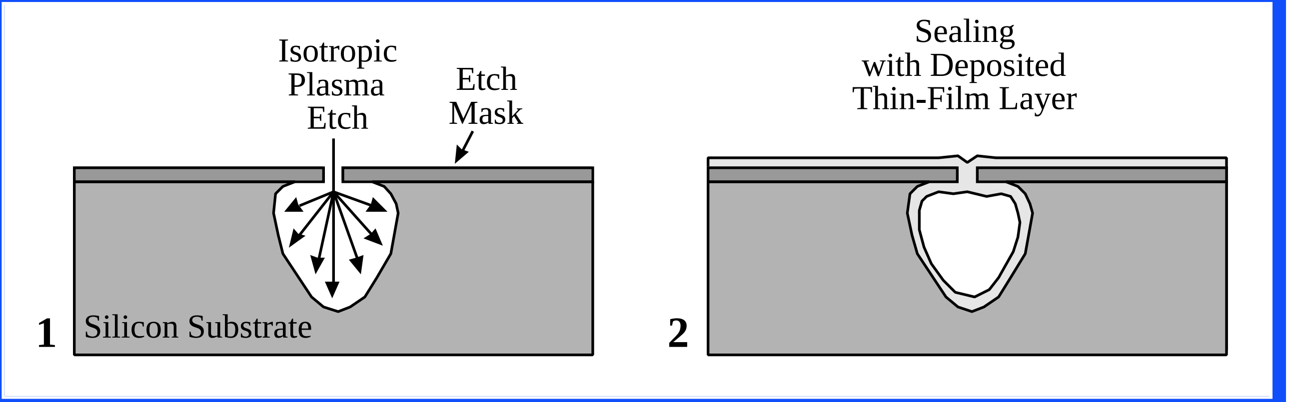
THIN-FILM FLOW CHANNELS



Reference: Tjerkstra, R. W., de Boer, M., Berenschot, E., Gardeniers, J. G. E., van den Berg, A., and Elwenspoek, M., "Etching Technology for Microchannels," Proceedings of the 10th Annual Workshop of Micro Electro Mechanical Systems (MEMS '97), Nagoya, Japan, Jan. 26 - 30, 1997, pp. 147 - 151.

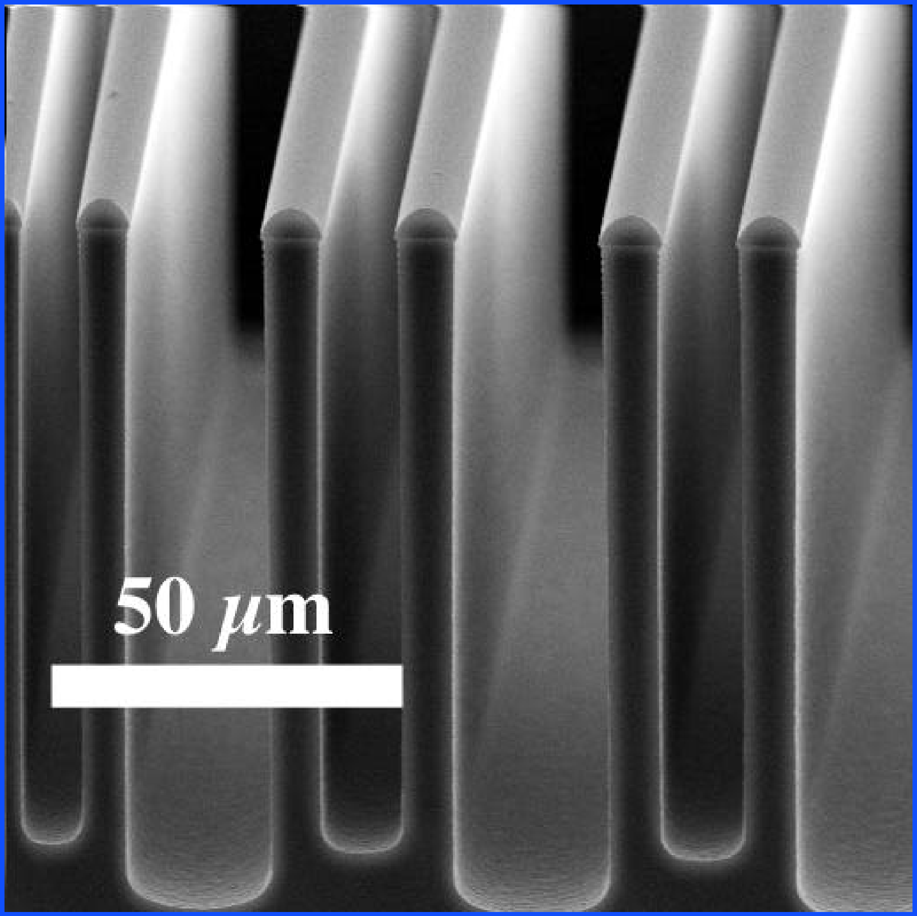
SELF-SEALING CHANNELS

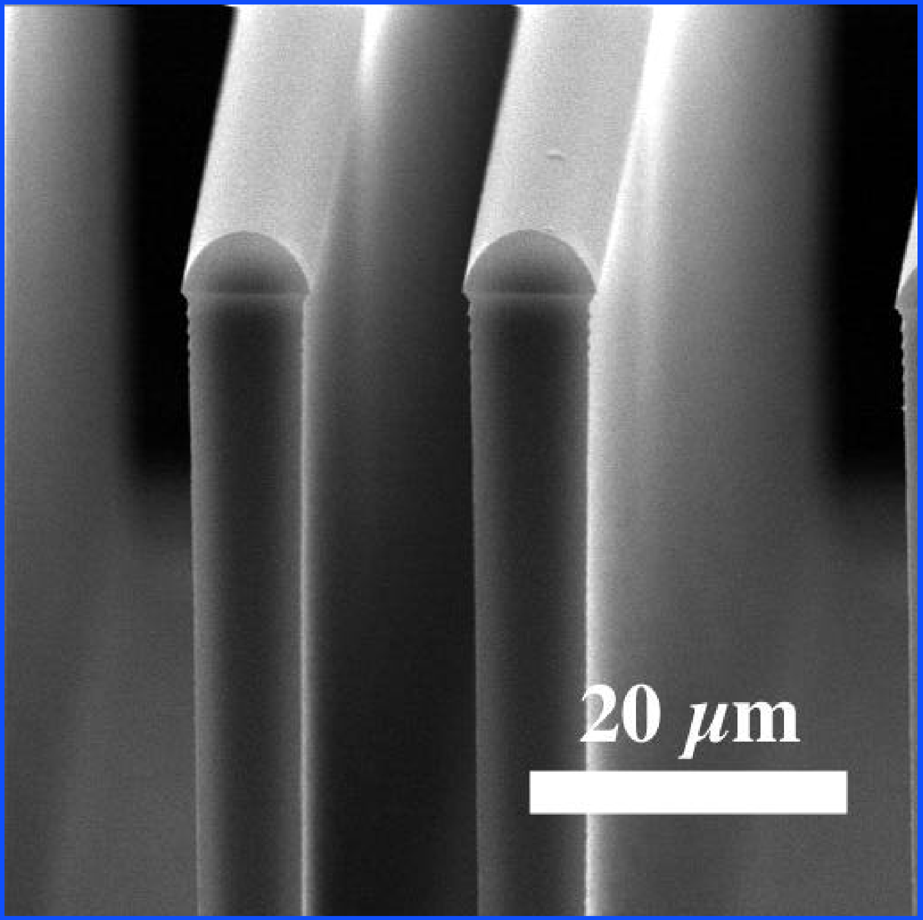




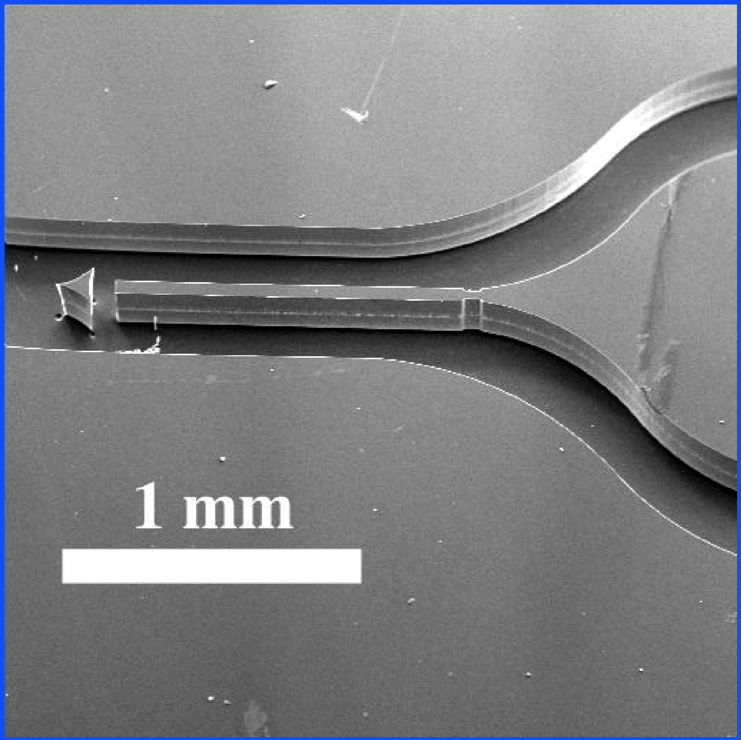
Courtesy A. Flannery, Stanford University.

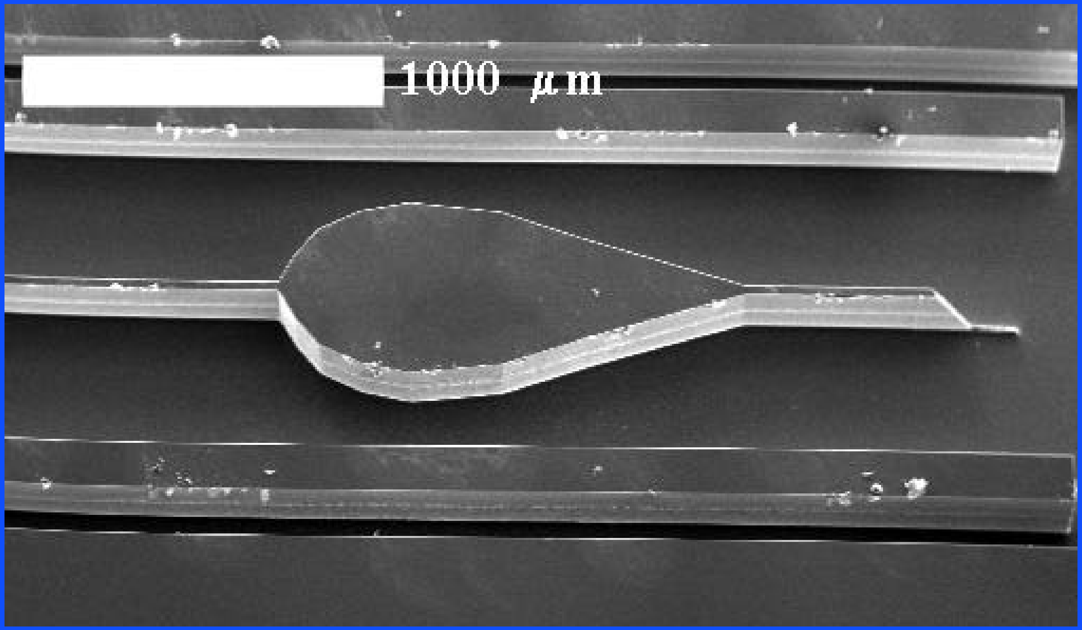
DRIE FLUIDIC CHANNELS





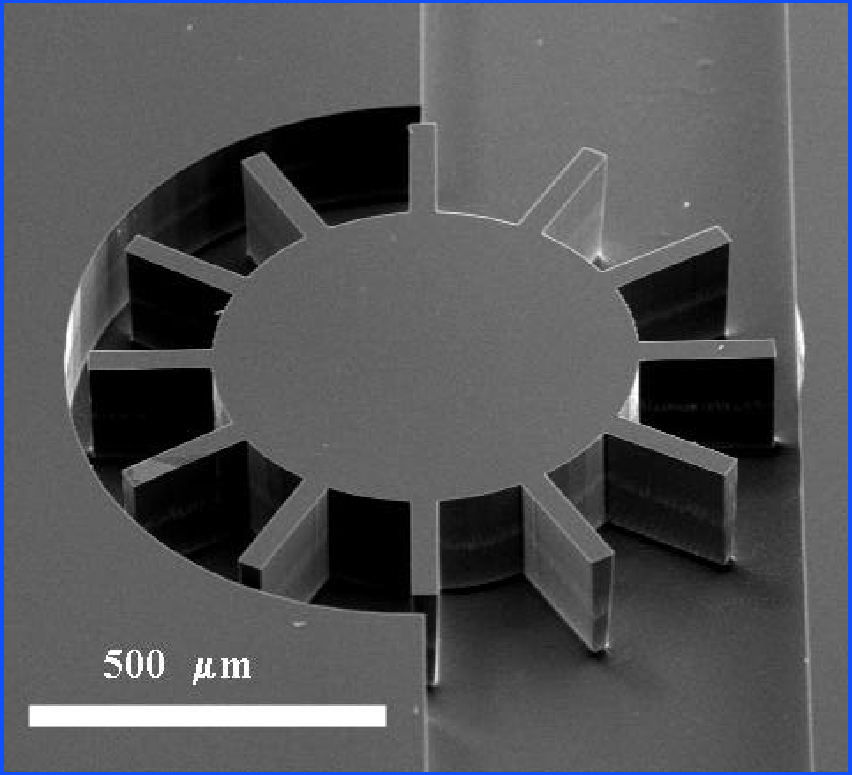
BASIC FLUIDIC FUNCTIONS

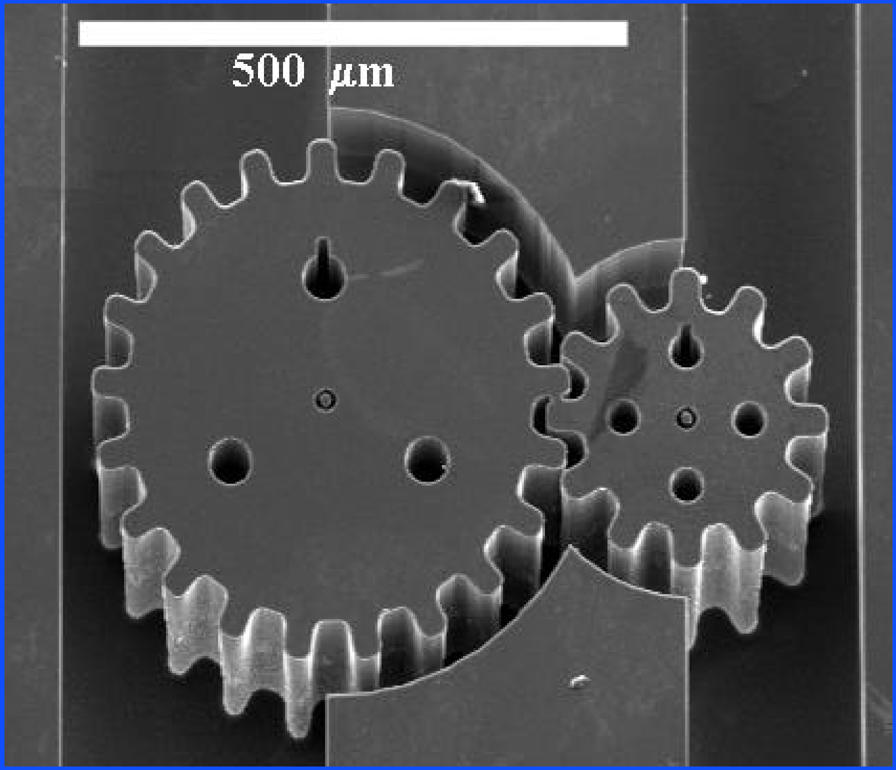




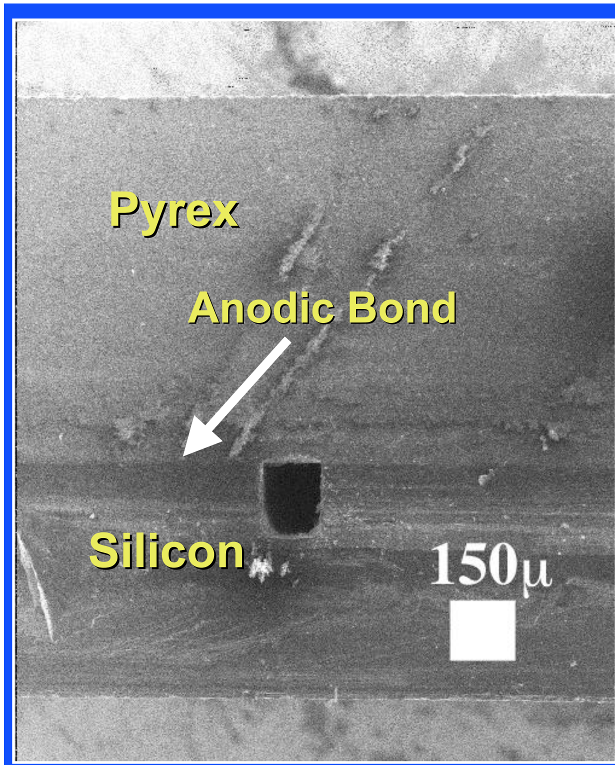
Mixer/splitter (left) and fluidic rectifier test structure (right).

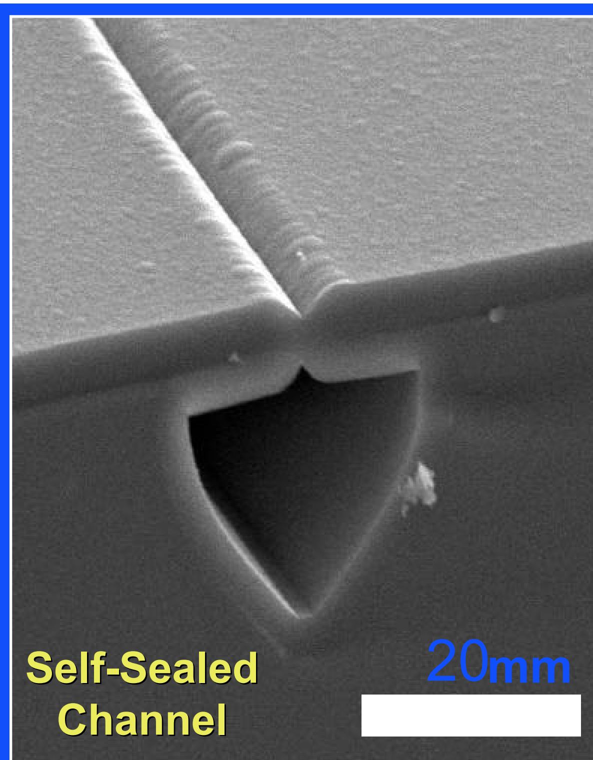
TOWARD FUTURE FLUIDIC MACHINES

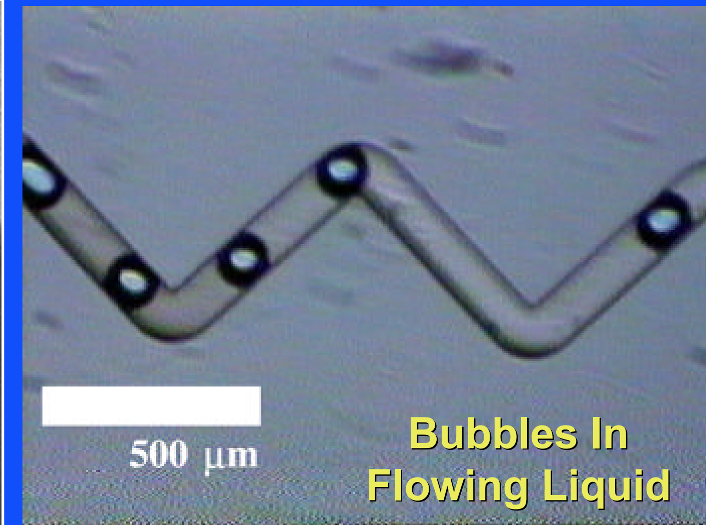


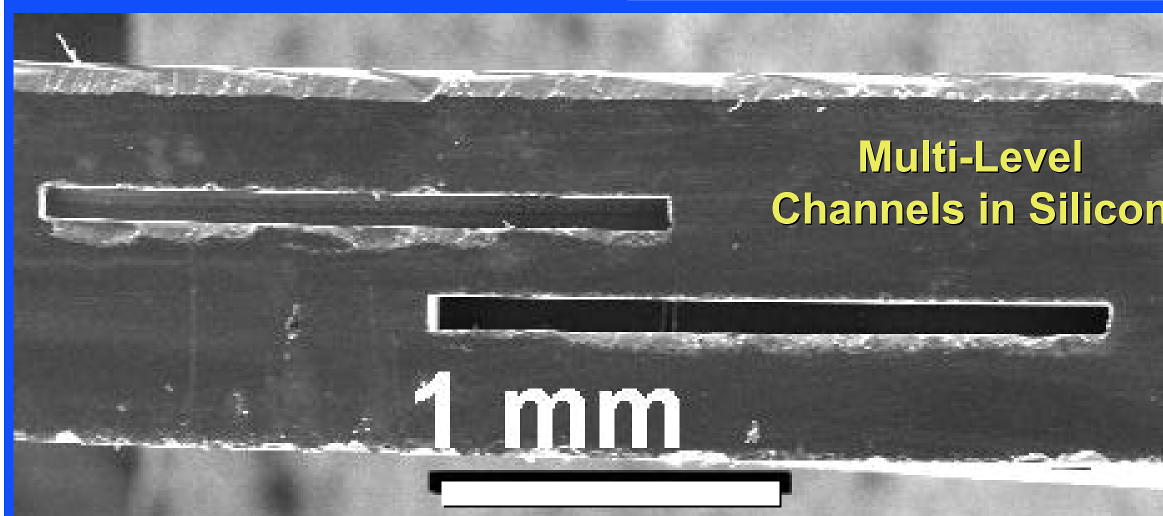


- **Using fusion bonding/DRIE, a wide variety of "active" fluidic structures are possible. Basic process capability is demonstrated.**



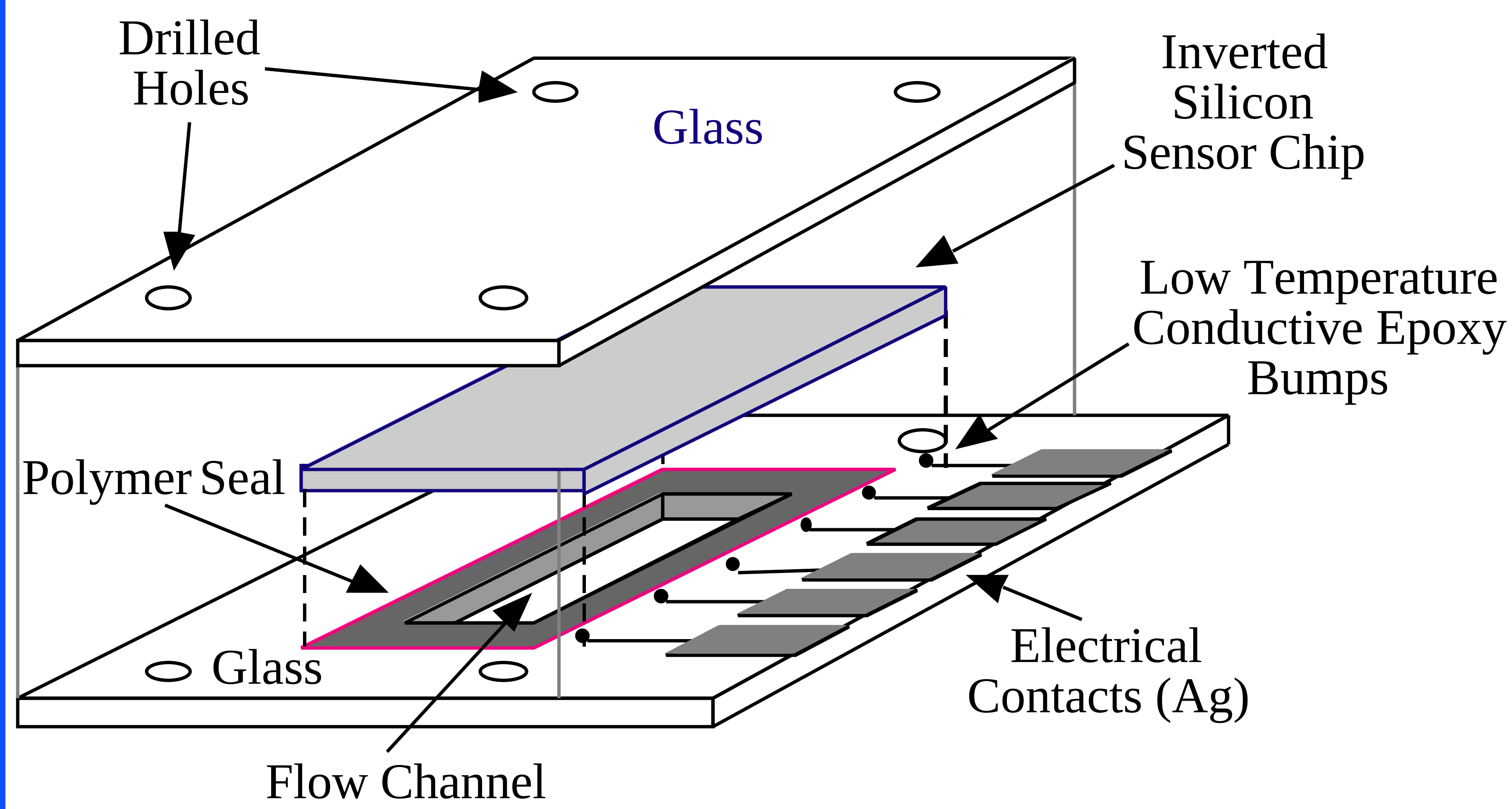






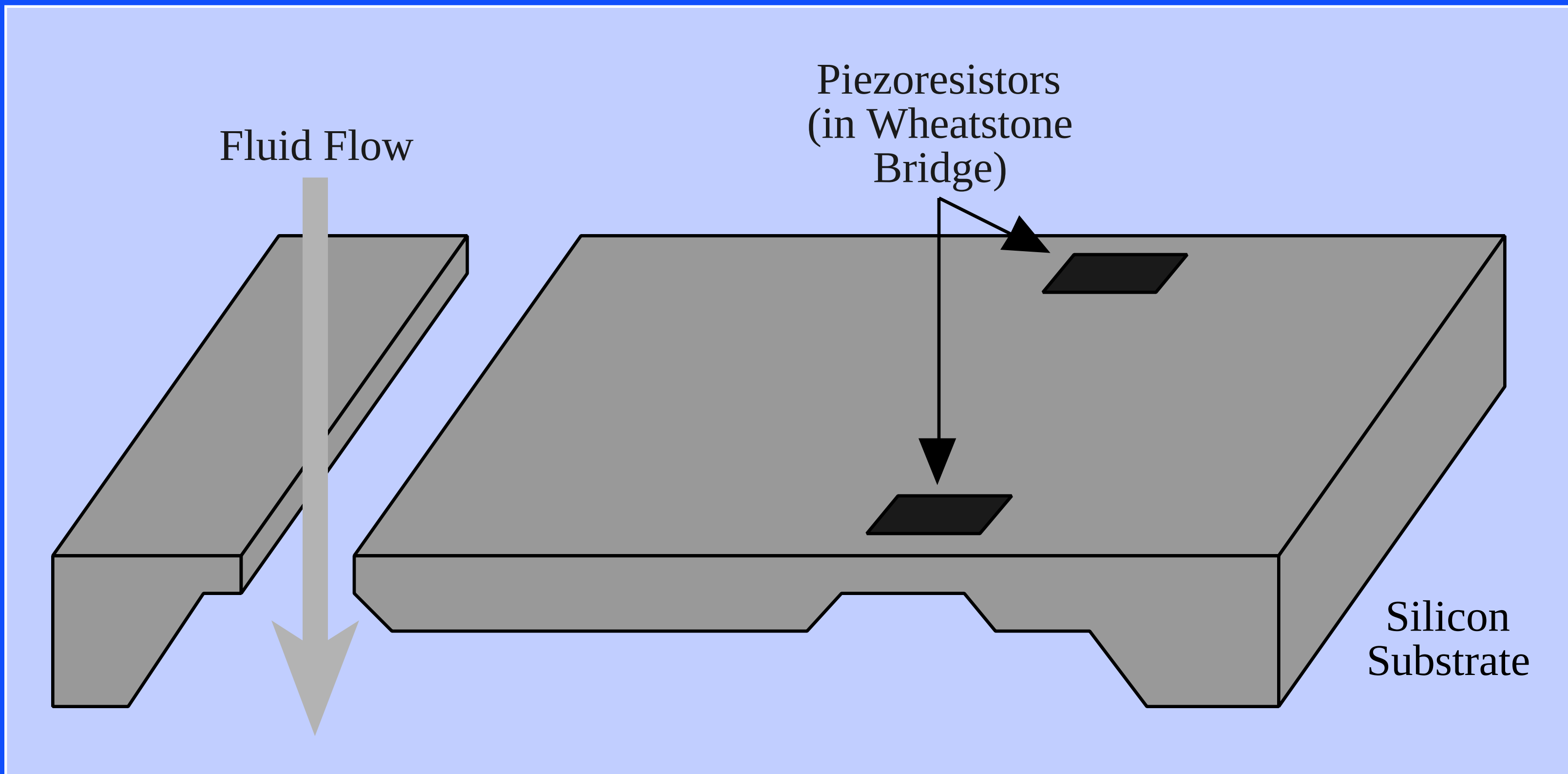
EXAMPLE MICROFLUIDIC CHANNEL STRUCTURES

HYBRID FLOW CHANNELS



Reference: Poplawski, M. E., Hower, R. W., and Brown, R. B., "A Simple Packaging Process for Chemical Sensors," Proceedings of the Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 25 - 28.

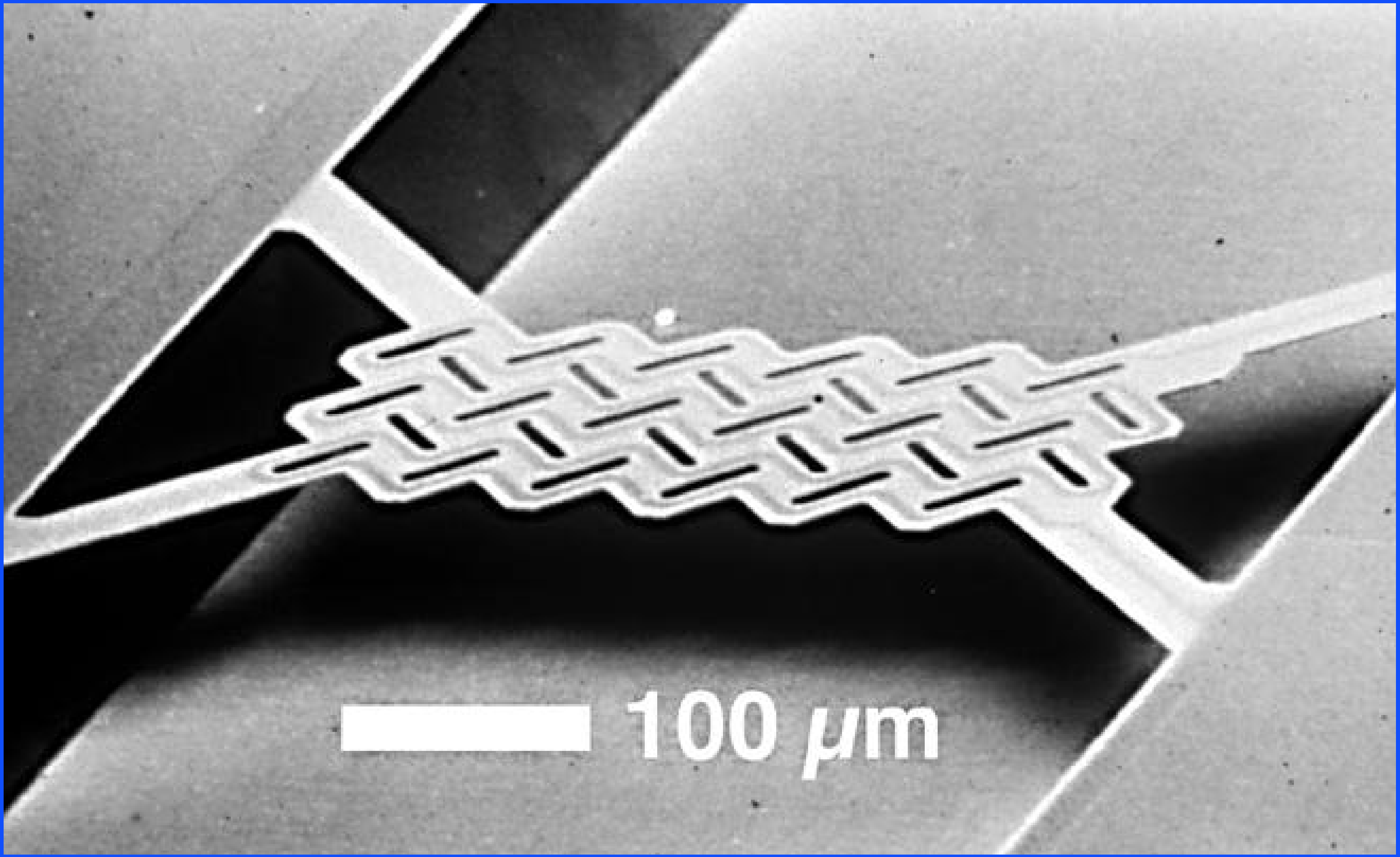
MECHANICAL (DRAG) FLOW SENSORS (FLUID INDEPENDENT)



Fluid-dependent flow sensors (i.e., thermal) are discussed in the "Thermal Transducers" section.

Reference: Gass, V., van der Schoot, B. H., and de Rooij, N. F., "Nanofluid Handling by Micro-Flow-Sensor Based on Drag Force Measurements," Proceedings of the IEEE MEMS Workshop, Ft. Lauderdale, FL, Feb. 1993, pp. 167 - 172.

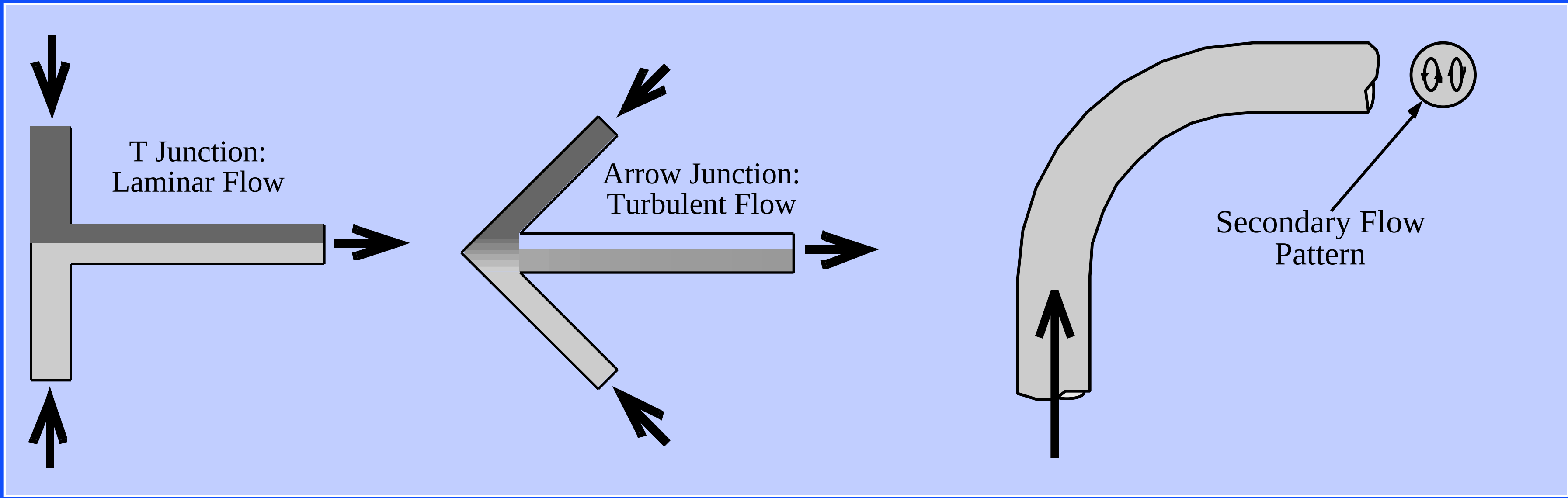
THERMAL FLOW SENSOR



Courtesy Prof. K. Petersen, Stanford University.

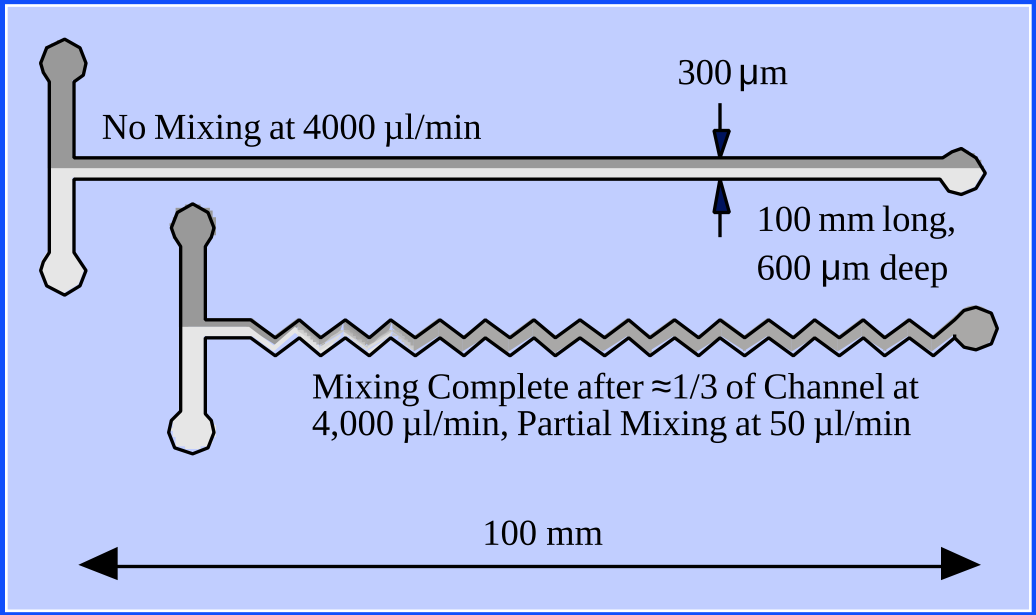
MIXING IN MICROSTRUCTURES

- Since flow is generally laminar, mixing tends to be by diffusion.
- However, some structures encourage turbulence.
- “V”-shaped corners can perform this function, as can centripetal acceleration around small radius curves.



Courtesy Dr. P. Krulevitch, Lawrence Livermore National Laboratory.

MIXING EXPERIMENTS

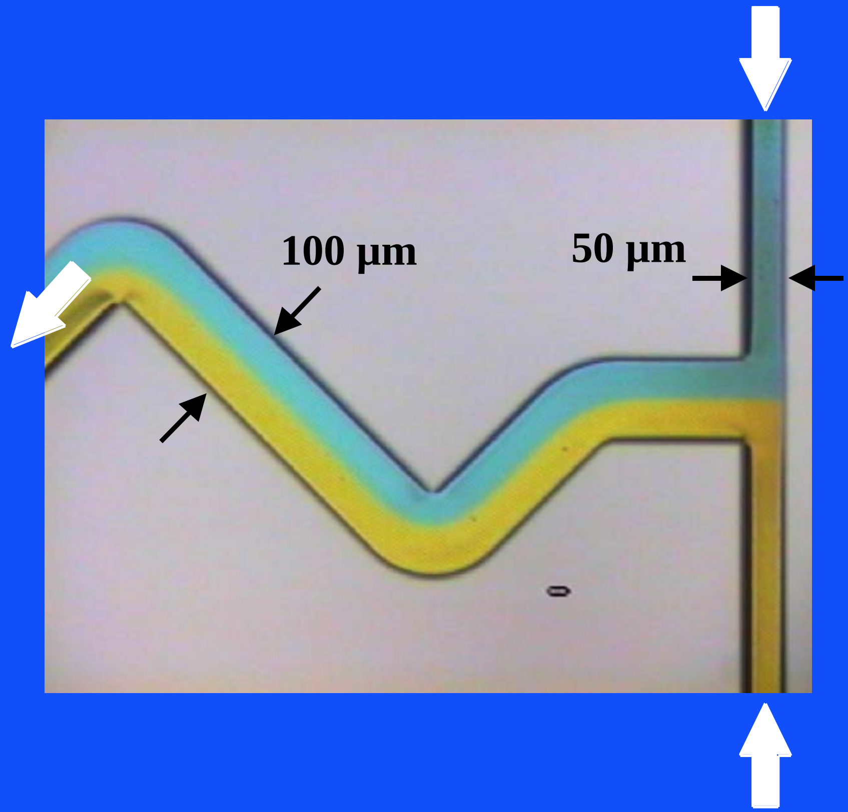


- **Experiments in microchannels showed that in "mini" channels (shown above), mixing was effectivly induced by "switchbacks."**
- **In "micro" channels (5 mm long, 180 µm width, 25 µm depth), *mixing was by diffusion only*.**

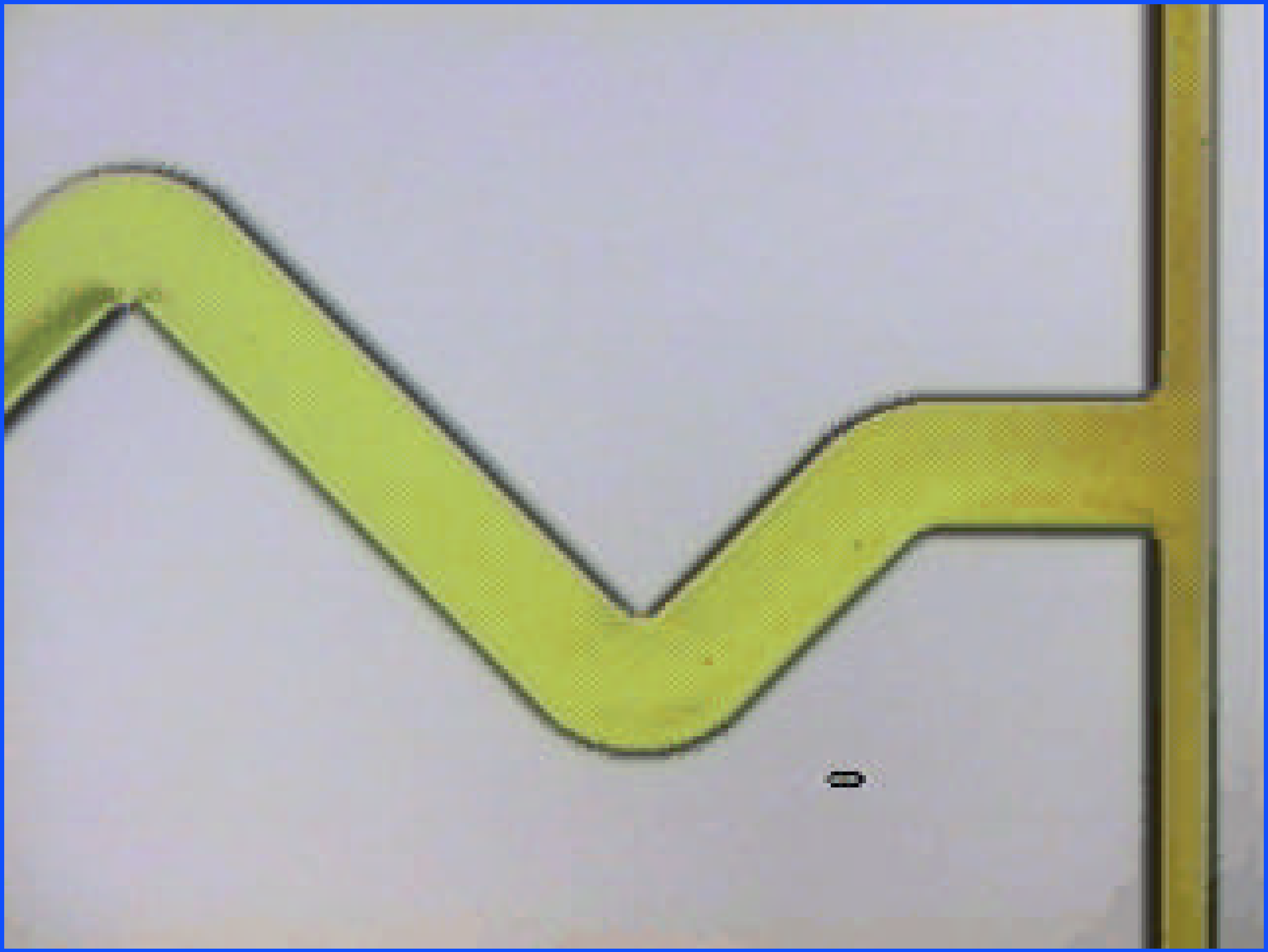
Reference: Branebjerg, J., Fabius, B., and Gravesen, P., "Application of Miniature Analyzers from Microfluidic Components to µTAS," van den Berg, A., and Bergveld, P. [eds.], Proceedings of Micro Total Analysis Systems Conference, Twente, Netherlands, Nov. 21 - 22, 1994, pp. 141 - 151.

FLOWS AT LOW REYNOLDS NUMBER

Q = 10 µl/min
v = 67 mm/s
R_e = 4.4



Two parallel streams of dyed water showing mixing by diffusion only.



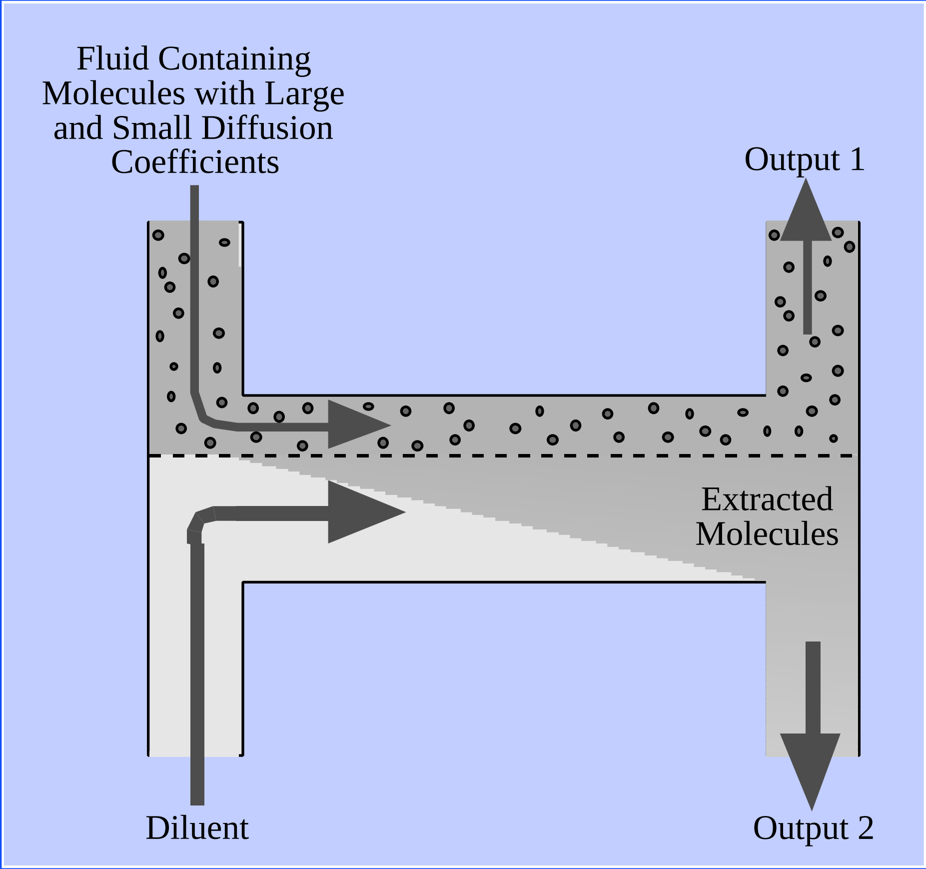
Courtesy Dr. D. Jaeggi, Stanford University.

EXAMPLE DIFFUSION COEFFICIENTS

Molecule	**Molecular Weight,** AMU	**Diffusion Coefficient in Water,** $\mu m^2/s$
H^+	1	9,000
Na^+	23	2,000
O_2	32	1,000
Glycine	75	1,000
Hemoglobin	6×10^4	70
Myosin	4×10^5	10
Tobacco Mosaic Virus	4×10^7	5

Reference: Brody, J. P., and Yager, P., "Diffusion-Based Extraction in a Microfabricated Device," Sensors and Actuators, vol. A58, no. 1, Jan. 1997, pp. 13 - 18.

DIFFUSION-BASED EXTRACTORS



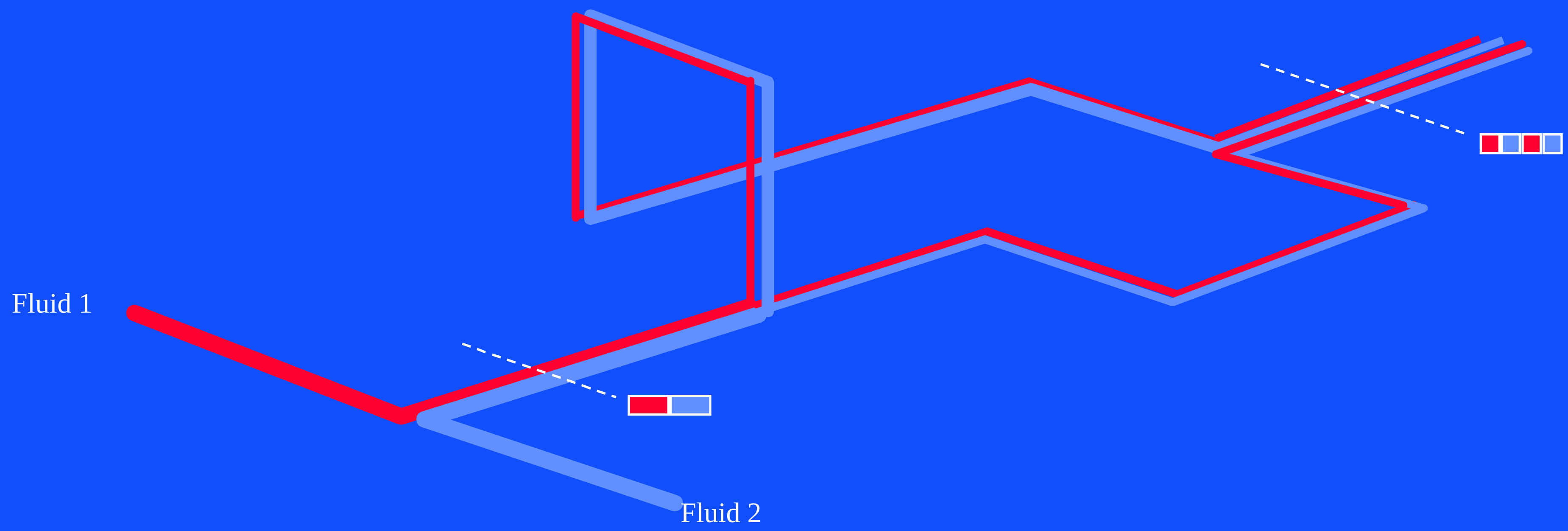
Reference: Brody, J. P., and Yager, P., "Diffusion-Based Extraction in a Microfabricated Device," Sensors and Actuators, vol. A58, no. 1, Jan. 1997, pp. 13 - 18.

LAMINATING MIXERS

- Branebjerg, et al. (1996) showed that by "folding" a pair of fluid flows into a stack of very thin sheets, diffusion could result in relatively fast mixing for the micro scale.
- The importance of this is that such mixing is accomplished without turbulence, which is not practically possible to create.

Reference: Brenebjerg, J., Gravesen, P., Krog, J. P., and Nielsen, C. R., "Fast Mixing by Lamination," Proceedings of the 9th Annual Workshop on Micro Electro Mechanical Systems, San Diego, CA, Feb. 11 - 15, 1996, pp. 441 - 446.

LAMINATING MIXER CONCEPT

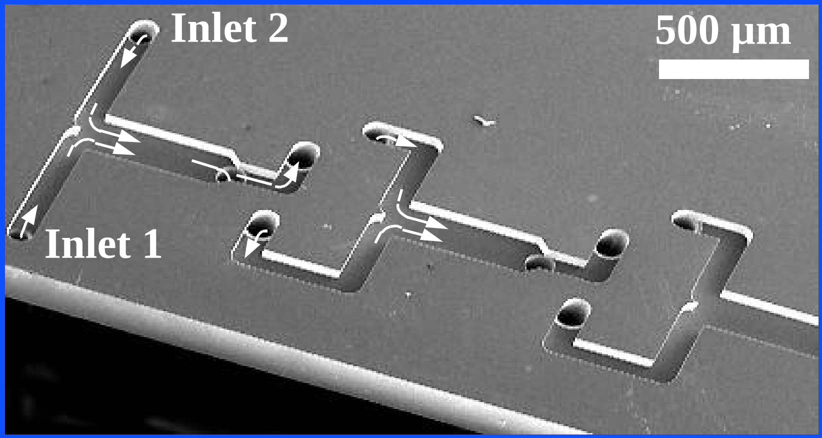


The laminar flows are separated and rejoined after a cross-over is performed using the second level of channels. Only one stage is shown here.

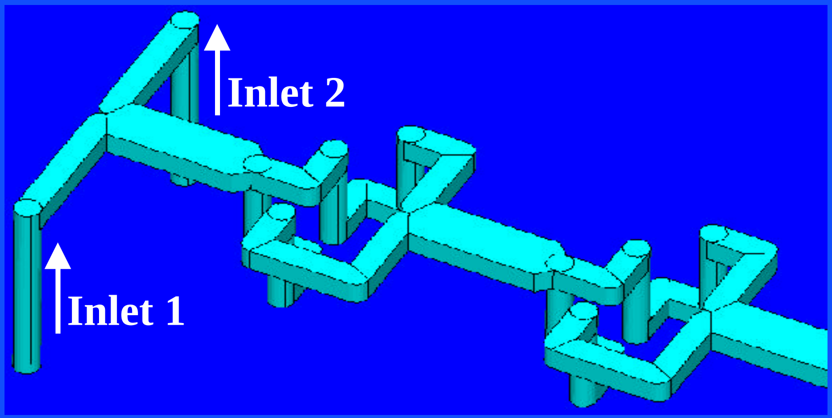
Courtesy Dr. D. Jaeggi, Stanford University.

LAMINATING MIXER

- SEM Photograph:

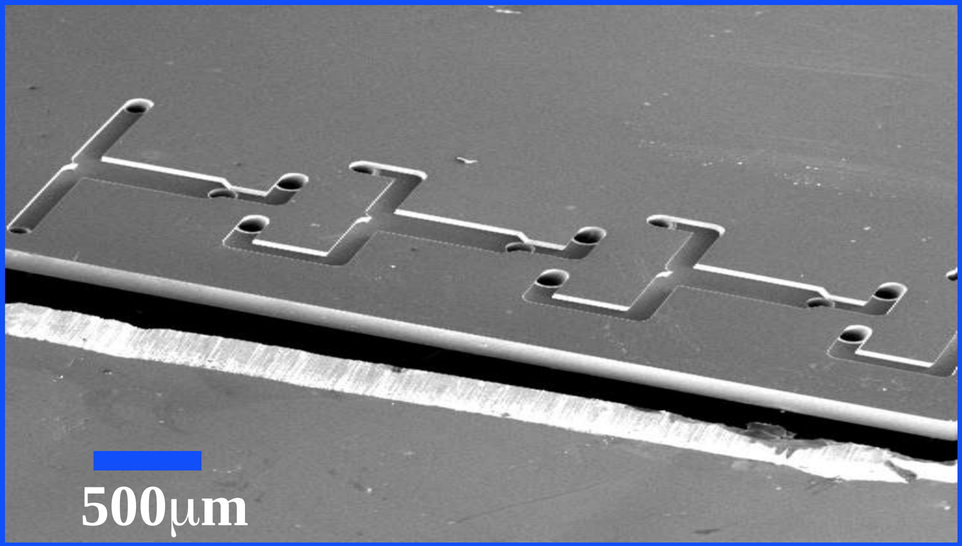


- Illustration of Multi-Levels:

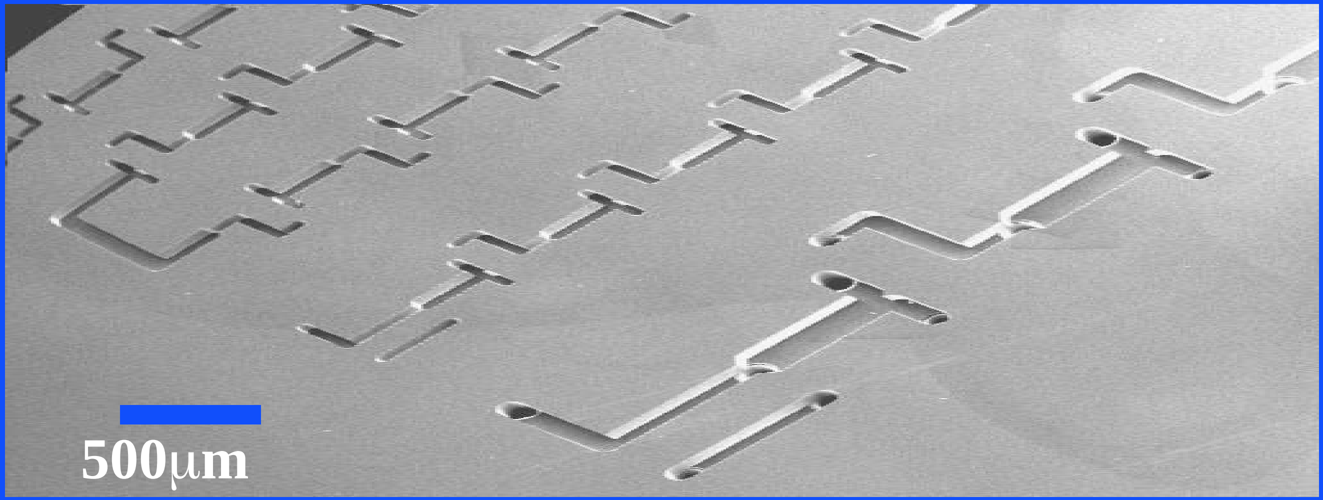


Courtesy Dr. D. Jaeggi, Stanford University.

LAMINATING MIXER: FABRICATION



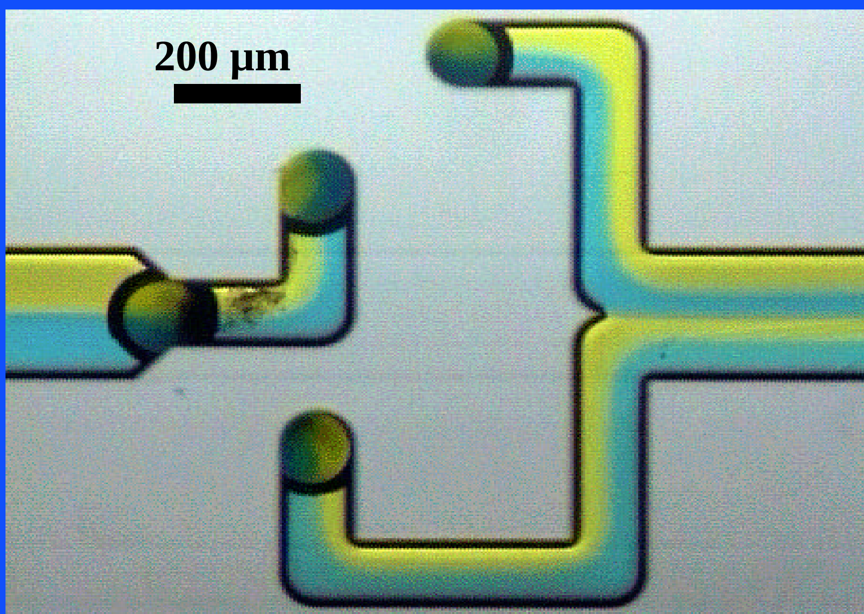
SEMs of top level of channels and vias of a multilevel mixing structure.



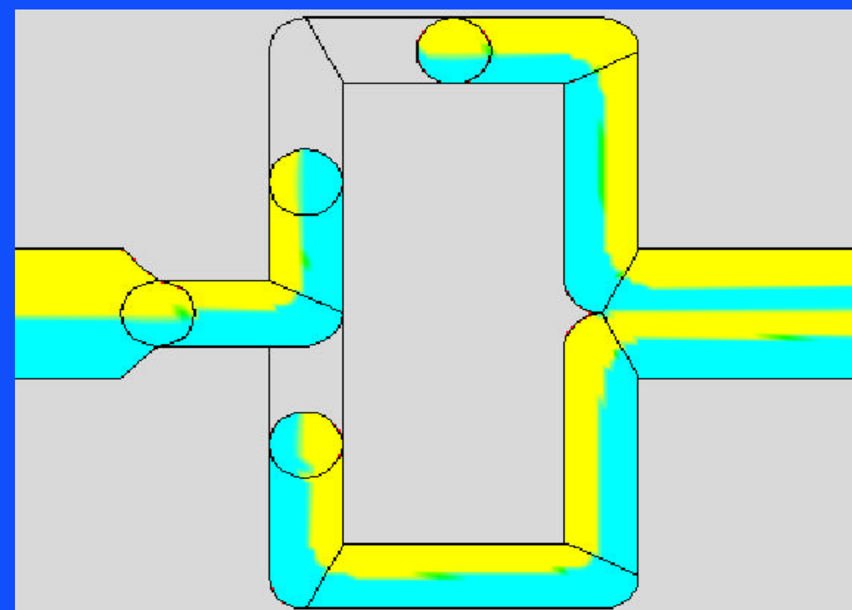
Courtesy Dr. D. Jaeggi, Stanford University.

LAMINATING MIXER: OPERATION

Experiment:

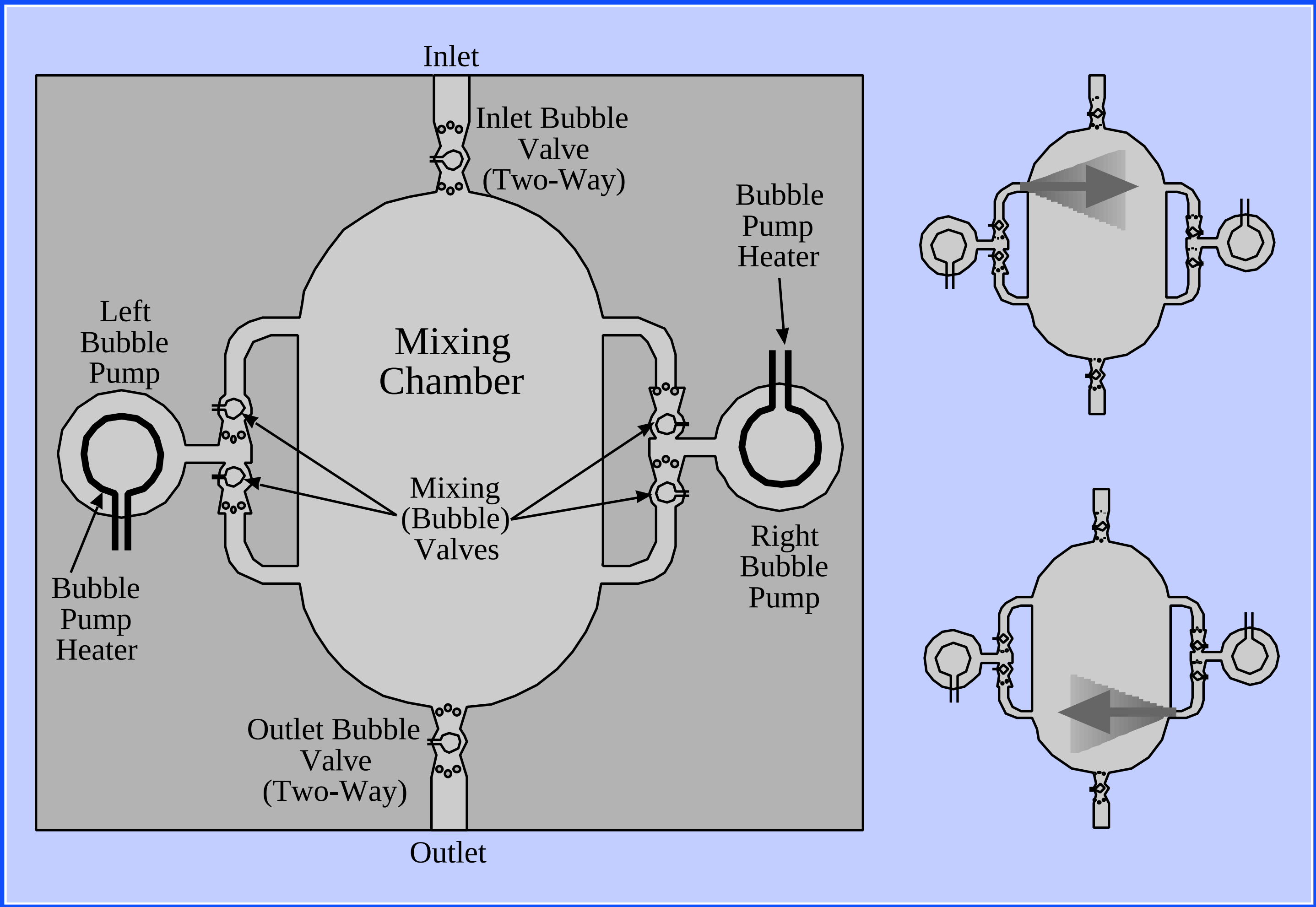


Simulation:



Courtesy Dr. D. Jaeggi, Stanford University.

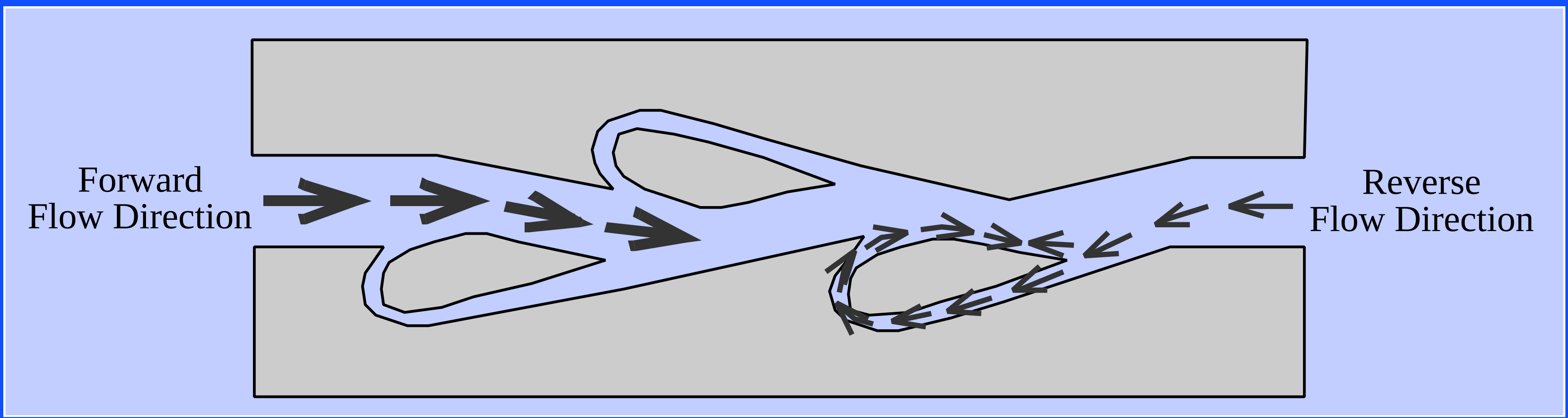
ACTIVE MIXERS (BUBBLE POWER)



Reference: Evans, J., Liepmann, D., and Pisano, A. P., "Planar Laminar Mixer," Proceedings of the IEEE 10th Annual Workshop of Micro Electro Mechanical Systems (MEMS '97), Nagoya, Japan, Jan. 26 - 30, 1997, pp. 96 - 101.

FLUIDIC AMPLIFIERS AND LOGIC

- Many operations ordinarily associated with electronic circuits can also be performed by fluidic devices, including amplification, logic functions, oscillators, etc.

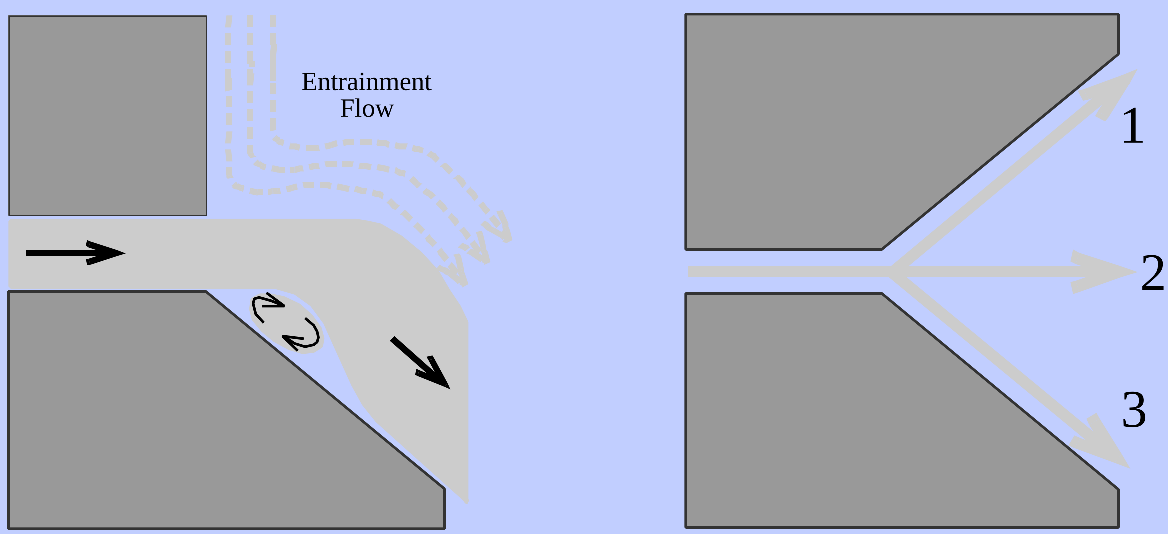


Tesla's "valvular conduit" (fluidic rectifier, 1920).

Reference: Humphrey, E. F., and Tarumoto, D. H. [eds.], "Fluidics," Fluid Amplifier Associates, Boston, MA, 1965.

THE COANDA EFFECT

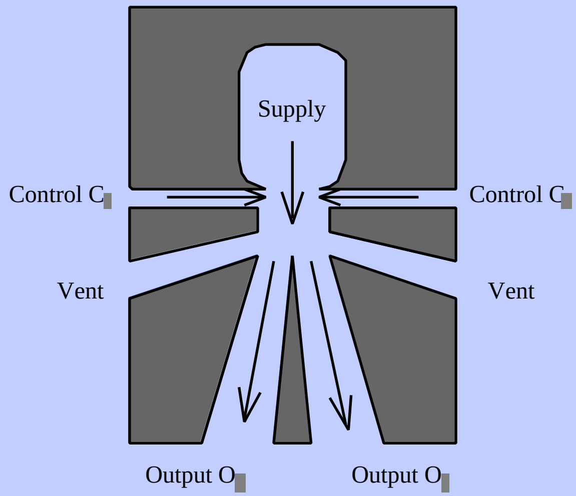
- Jet streams of fluid tend to capture or “entrain” adjacent fluid molecules.
- When the jet is near to a surface, the supply of “entrainable” molecules decreases, forming a low pressure region and drawing the jet toward the surface (following it).
- Many fluidic circuits make use of this effect (Coanda (1934)).



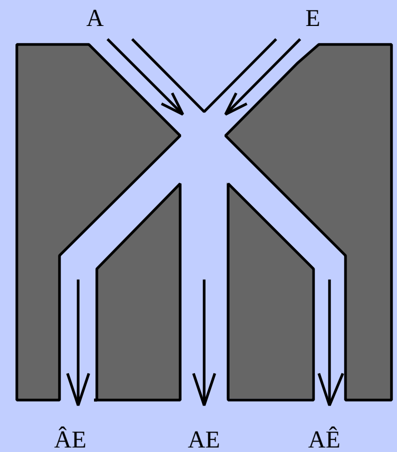
Three stable states for a wide angle output (“diffuser”) diffuser for a jet.

Reference: Humphrey, E. F., and Tarumoto, D. H. [eds.], “Fluidics,” Fluid Amplifier Associates, Boston, MA, 1965.

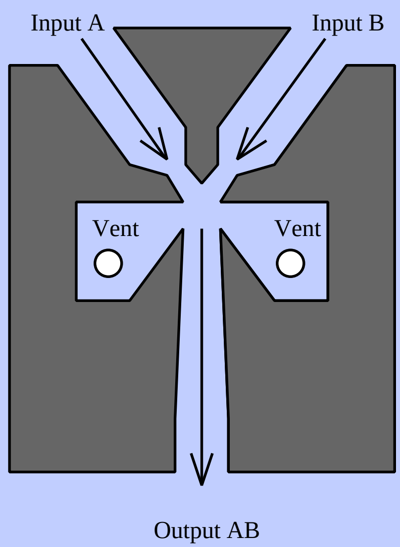
Proportional (Analog) Amplifier



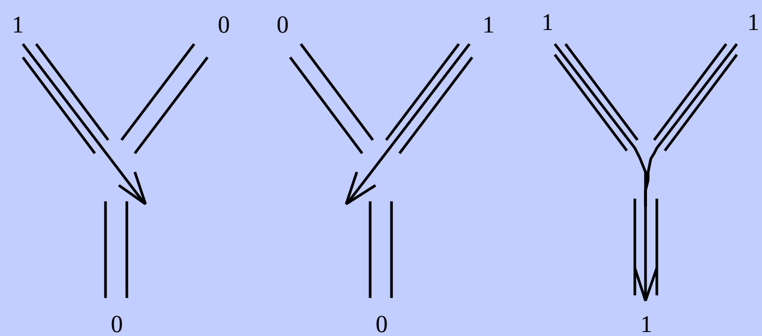
Digital Half-Adder



Digital AND Gate



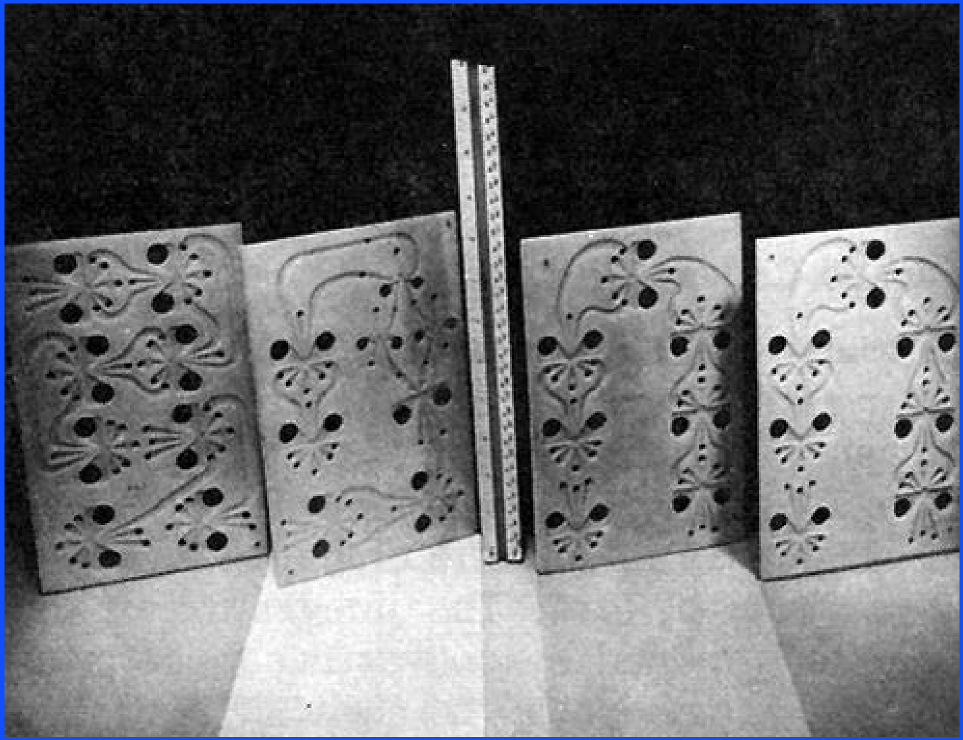
AND Gate Fluid Flow Combinations ("Truth Table")



(An XOR function can be derived from the AND gate by connecting the vents and relabeling the inputs.)

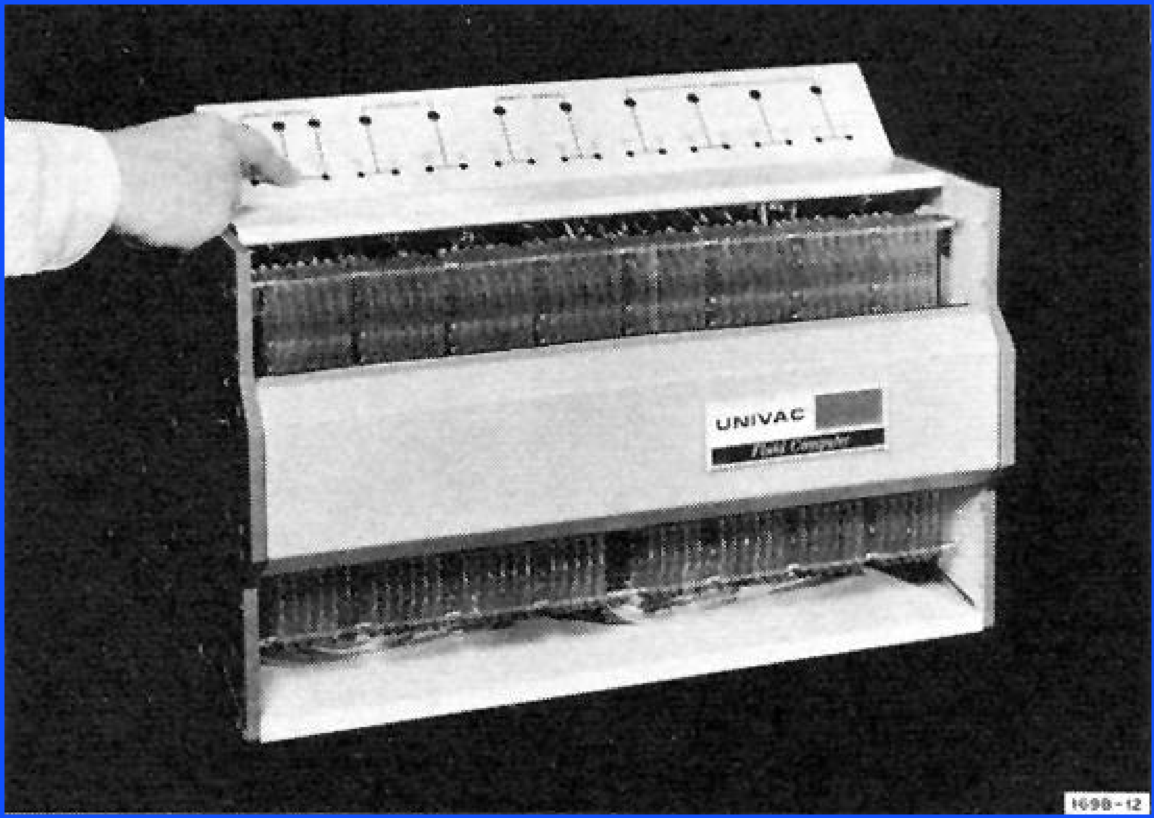
Reference: Foster, K., and Parker, G. A., "Fluidics: Components and Circuits," Wiley Interscience, New York, NY, 1970.

FLUIDIC MIN/MAX CIRCUIT



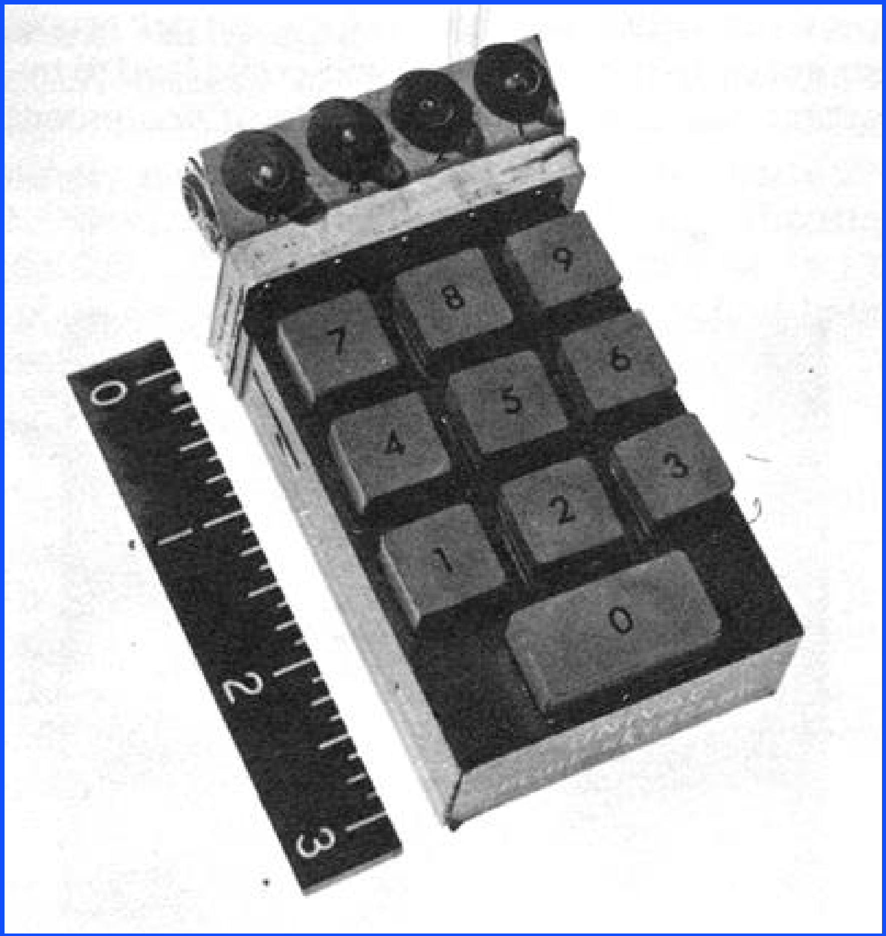
Source: Foster, K., and Parker, G. A., “Fluidics: Components and Circuits,” Wiley Interscience, New York, NY, 1970.

FLUIDIC COMPUTER (UNIVAC)



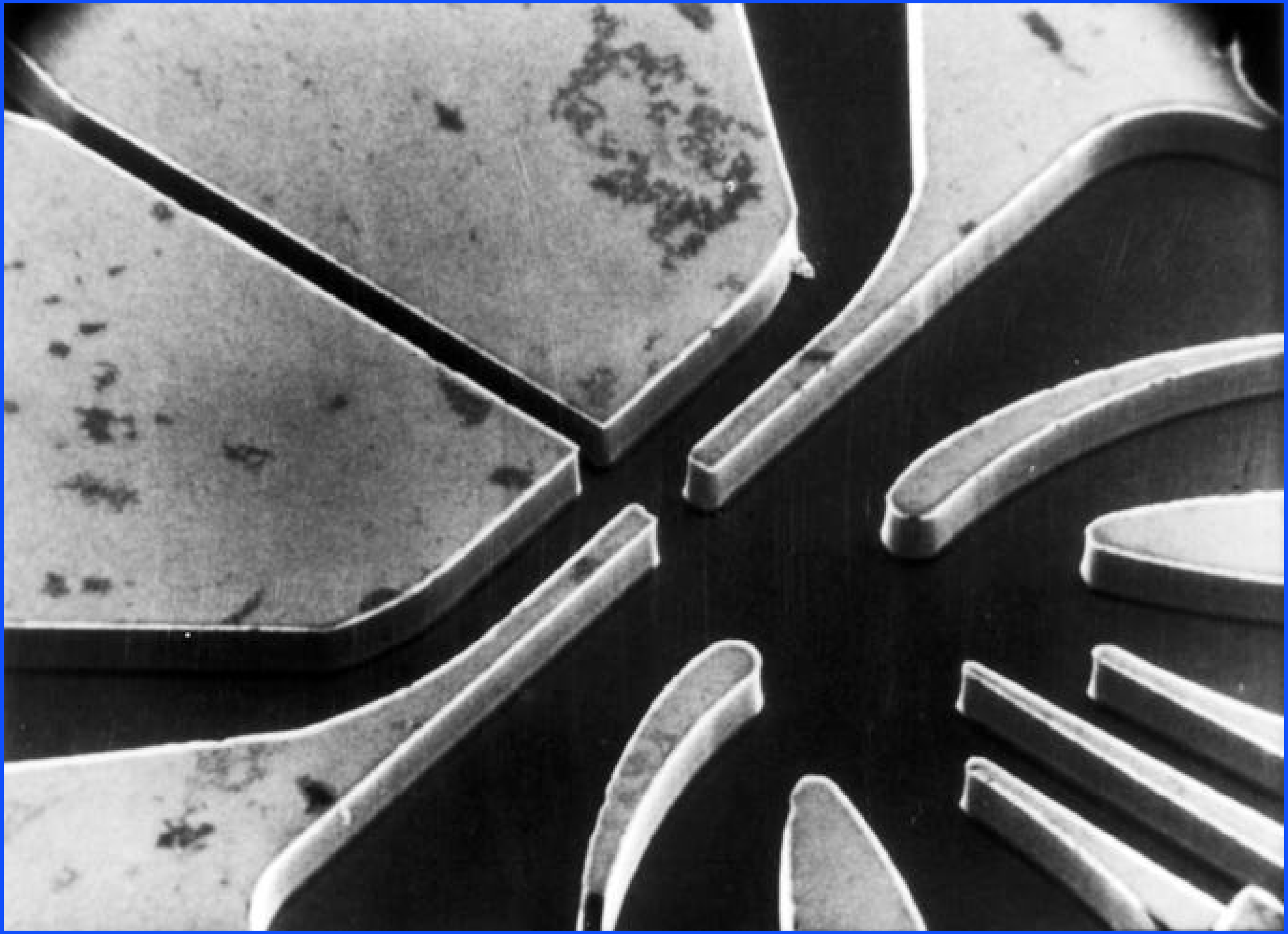
Source: Jacoby, M., “Digital Applications of Fluid Amplifiers,” in “Fluidics,” Humphrey, E. F., and Tarumoto, D. H. [eds.], Fluid Amplifier Associates, Boston, MA, 1965, pp. 240 - 249.

FLUIDIC COMPUTER (UNIVAC)



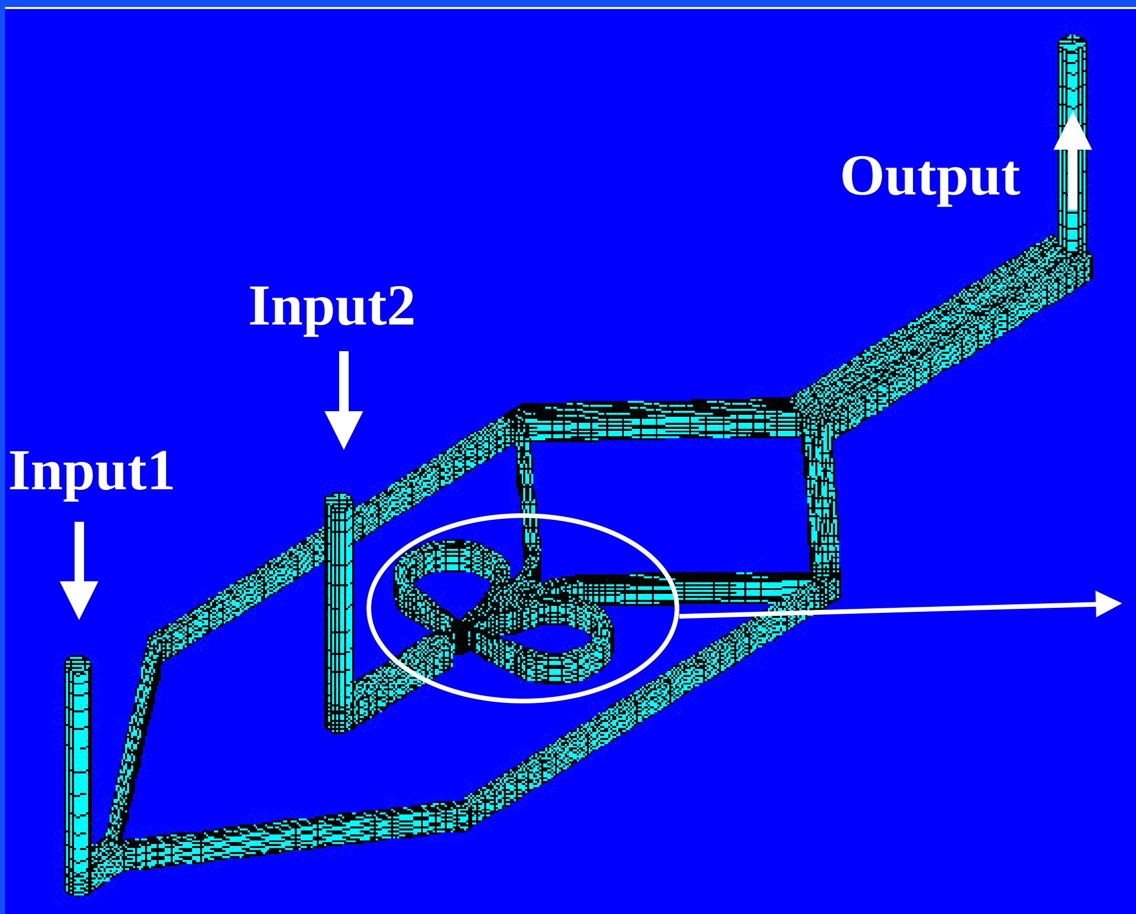
Source: Jacoby, M., “Digital Applications of Fluid Amplifiers,” in “Fluidics,” Humphrey, E. F., and Tarumoto, D. H. [eds.], Fluid Amplifier Associates, Boston, MA, 1965, pp. 240 - 249.

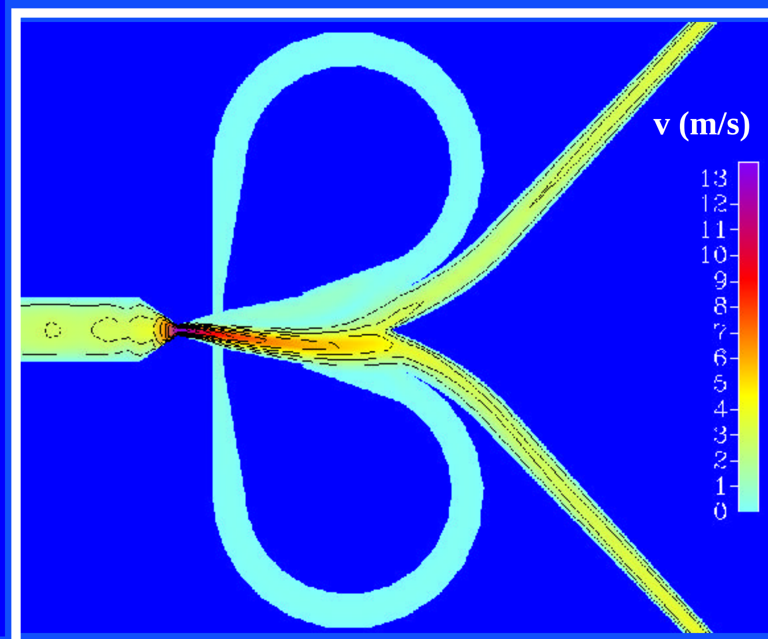
MICROMACHINED FLUIDIC AMPLIFIER



Courtesy Dr. M. Zdeblick, Redwood Microsystems. Reference: Zdeblick, M., J., and Angell, J. B., “Microminiature Fluidic Amplifier,” Sensors and Actuators, vol. 15, no. 4, Dec. 1988, pp. 427 - 433.

SELF-OSCILLATING MIXER



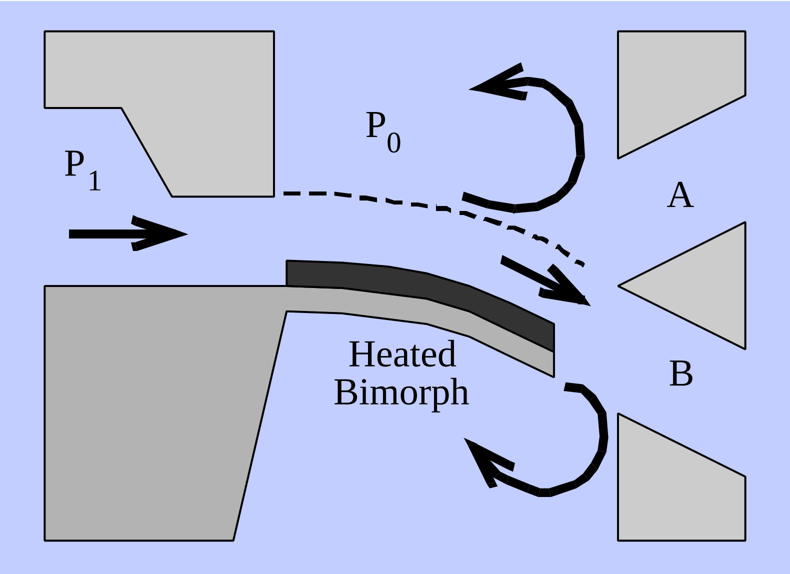


Courtesy Dr. D. Jaeggi, Stanford University.

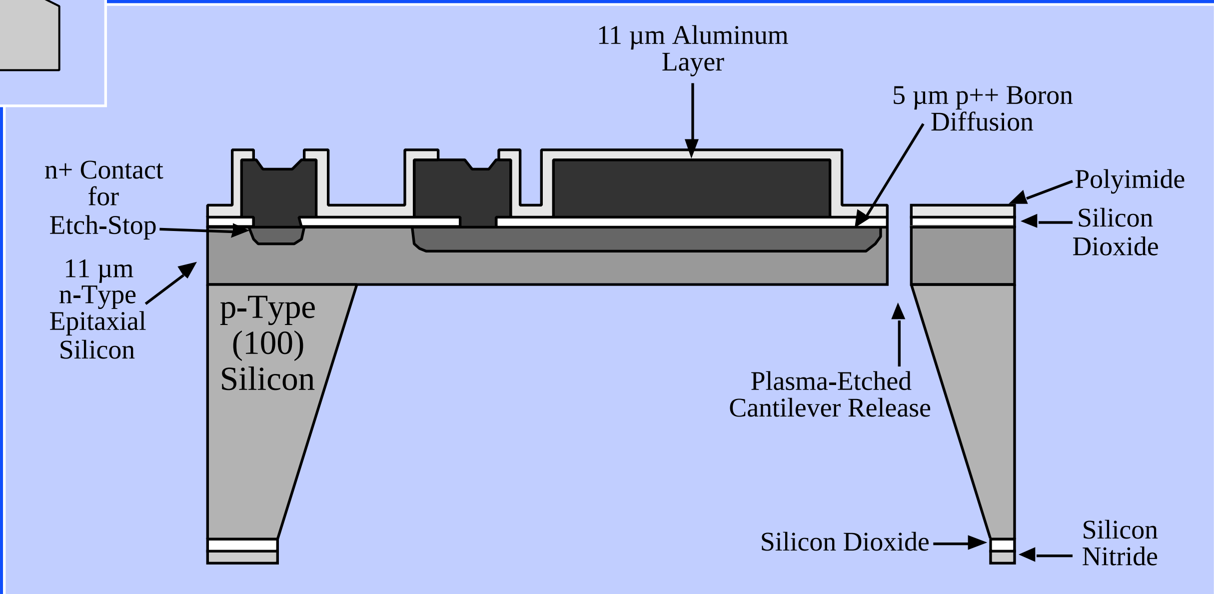
VALVES

- Ideal valve characteristics:
  - zero leakage
  - zero power consumption
  - zero dead volume
  - infinite differential pressure capability
  - insensitivity to particulate contamination
  - zero response time ("infinitely fast" state change)
  - potential for linear operation
  - ability to operate with liquids and gases of any density/viscosity/chemistry
  - others?
- In practice, one is faced with a trade-off.
- Valves are categorized as either "passive" or "active," depending upon whether or not they use external power to actuate.

COANDA EFFECT “VALVE”

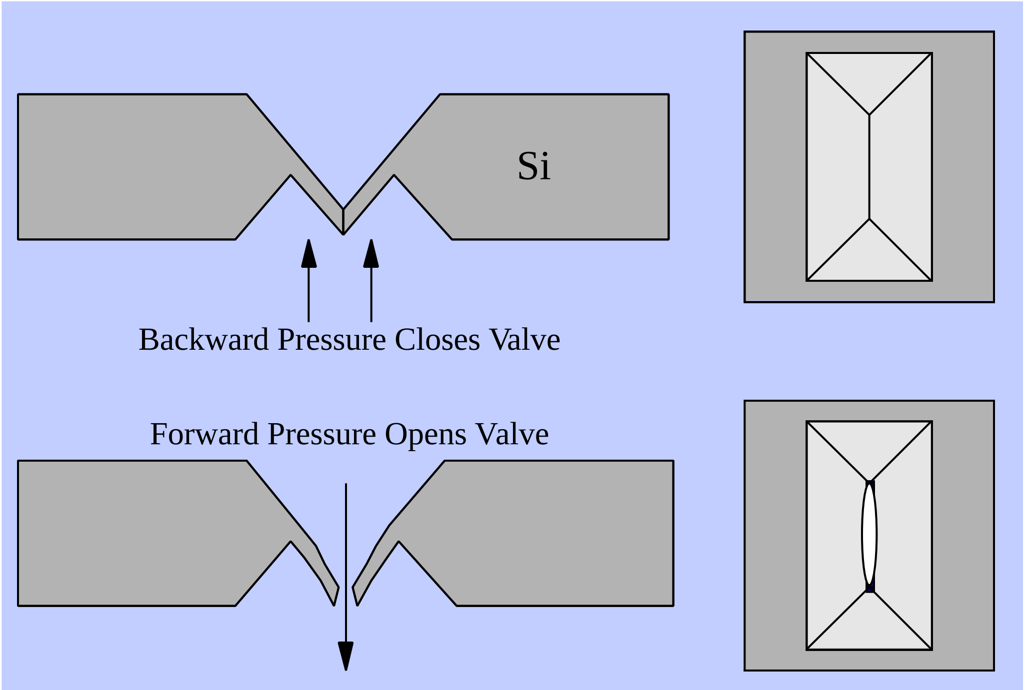


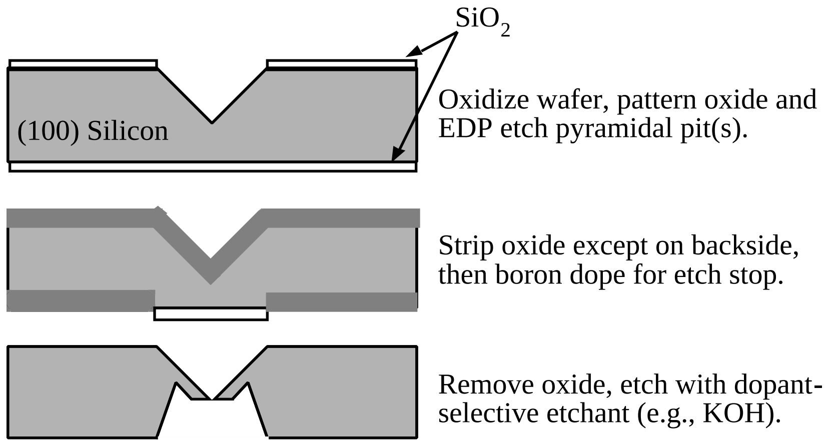
- **Döring, et al., used an Al/Si thermal bimorph actuator to “steer” a fluid jet using approximately 1W of power (obtaining 15° deflections).**
- **At pressures of 2 - 7 bar and flow rates of 100 - 150 ml/min, free water jets could be deflected with time constants on the order of 1 ms.**



Reference: Döring, C., Grauer, T., Marek, J., Mettner, M., Trah, H. P., and Willman, M., “Micromachined Thermoelectrically Driven Cantilever Beams for Fluid Deflection,” Proceedings of the IEEE Micro Electro Mechanical Systems Workshop (MEMS ’92), Travemünde, Germany, Feb. 4 - 7, 1992, pp. 12 - 18.

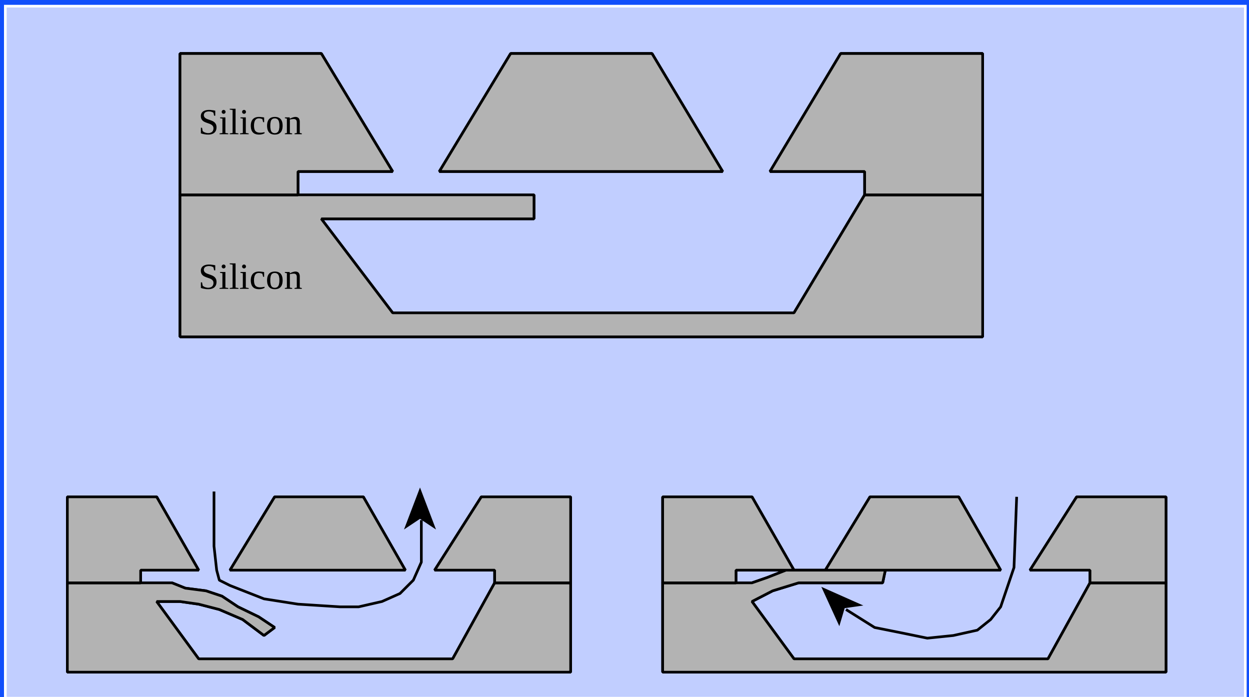
PASSIVE VALVES



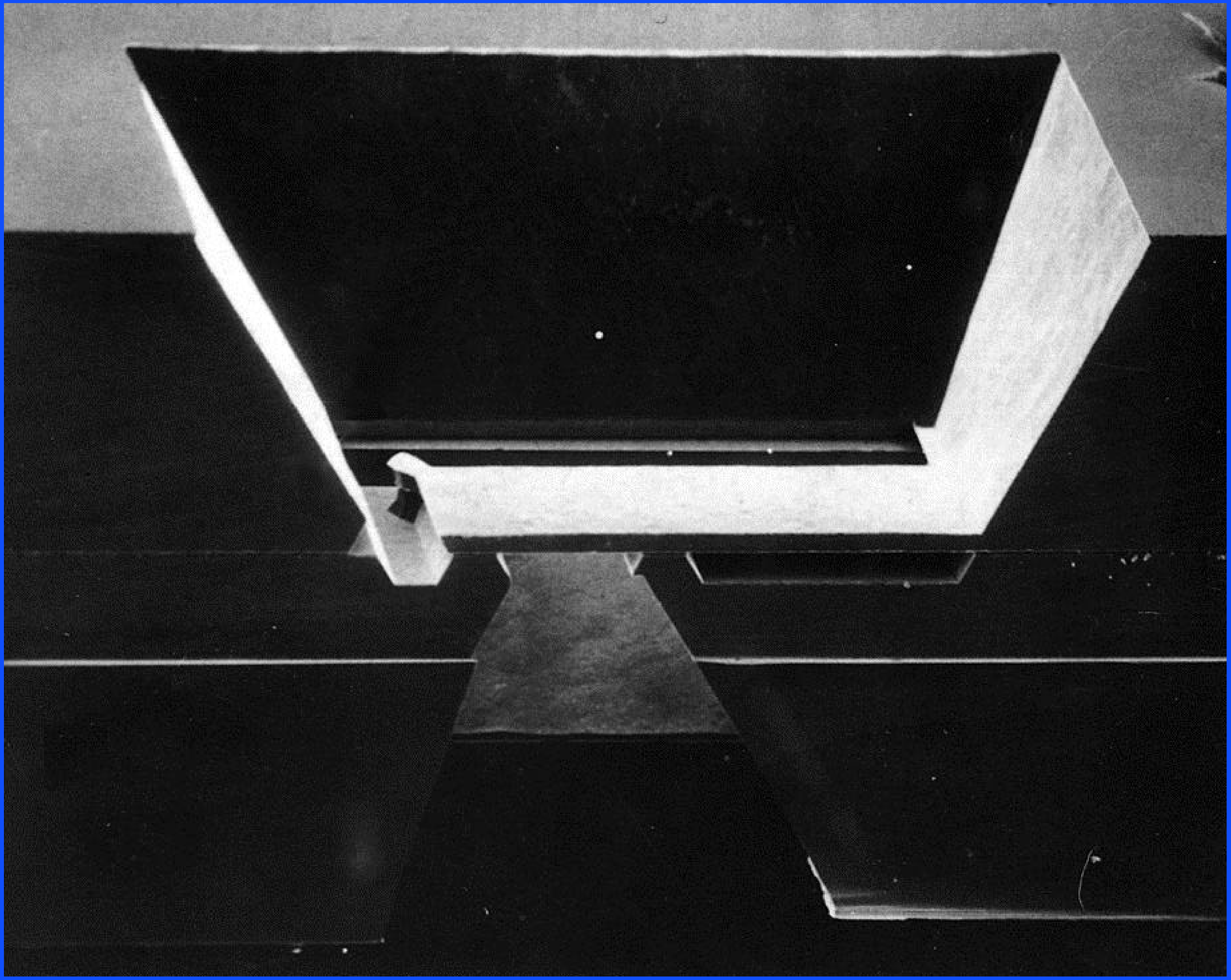


Reference: Smith, L., and Hök, B., "A Silicon Self-Aligned Non-Reverse Valve," Proceedings of Transducers '91, the 1991 International Conference on Solid-State Sensors and Actuators, San Francisco, CA, June 24 - 27, 1991, pp. 1049 - 1051.

WAFER-STACK PASSIVE VALVES

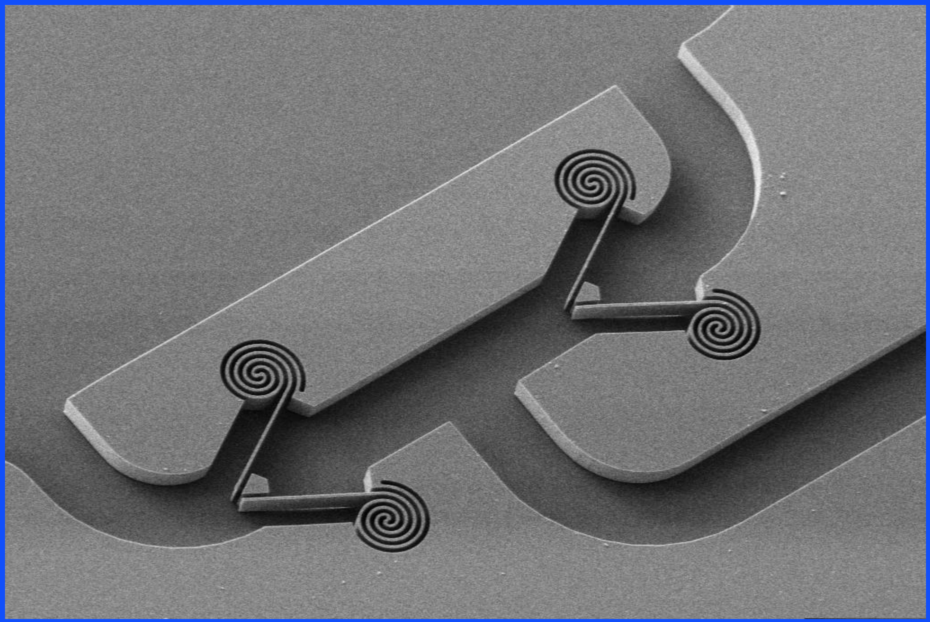


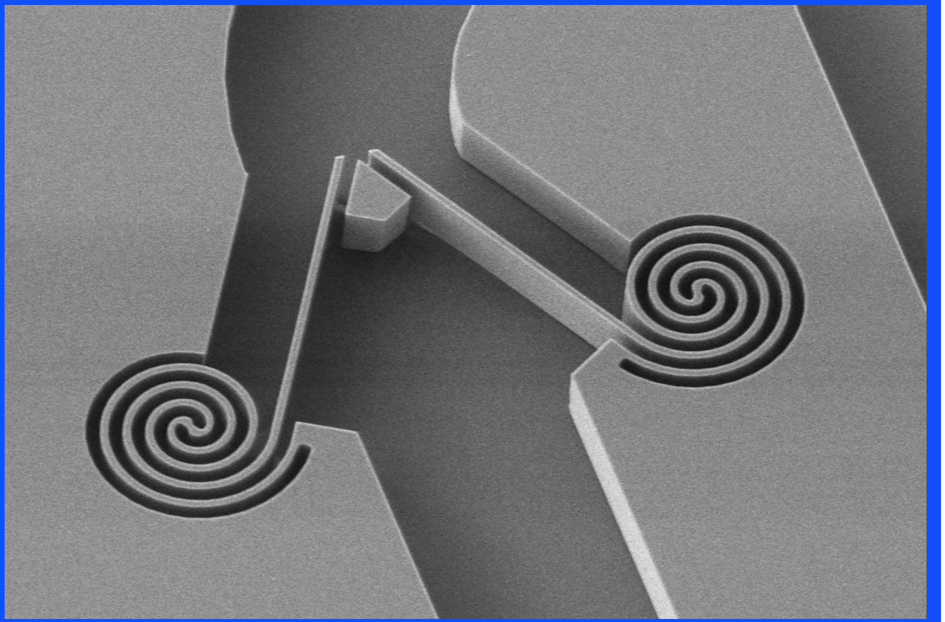
Reference: Tiren, J., Tenerz, L., and Hök, B., “A Batch-Fabricated Non-Reverse Valve with Cantilever Beam Manufactured by Micromachining of Silicon,” Sensors and Actuators, vol. 18, nos. 3 - 4, July 1989, pp. 398 - 396.



Source: Journal of Micromechanics and Microengineering.

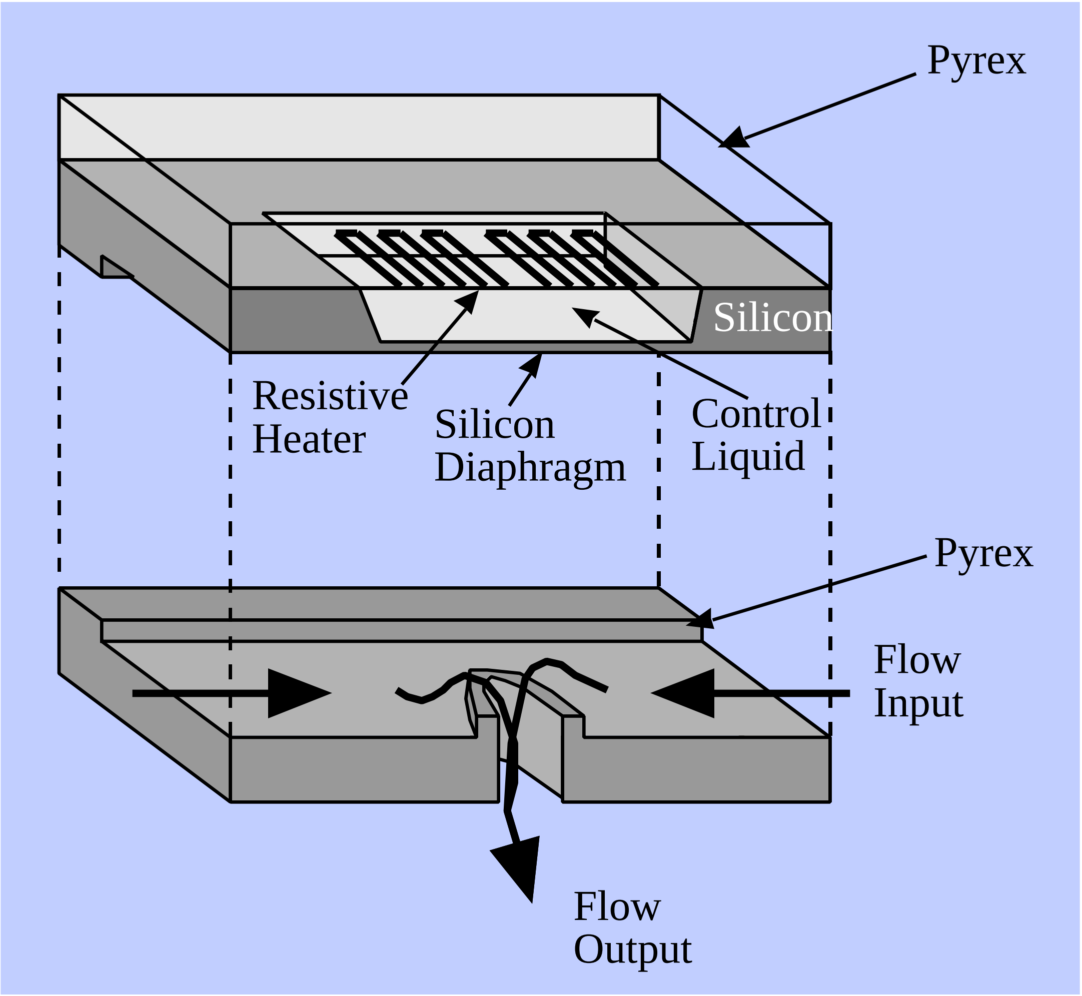
PLANAR CHECK VALVES





Courtesy Dr. J. Evans. Reference: Evans, J.; Liepmann, D.; “The ‘Spring Valve’ Mechanical Check Valve for In-Plane Fluid Control”, Transducers '99 (The 10th International Conference on Solid-State Sensors and Actuators). Sendai, Japan, June 7-10, 1999, p. 1796-1799.

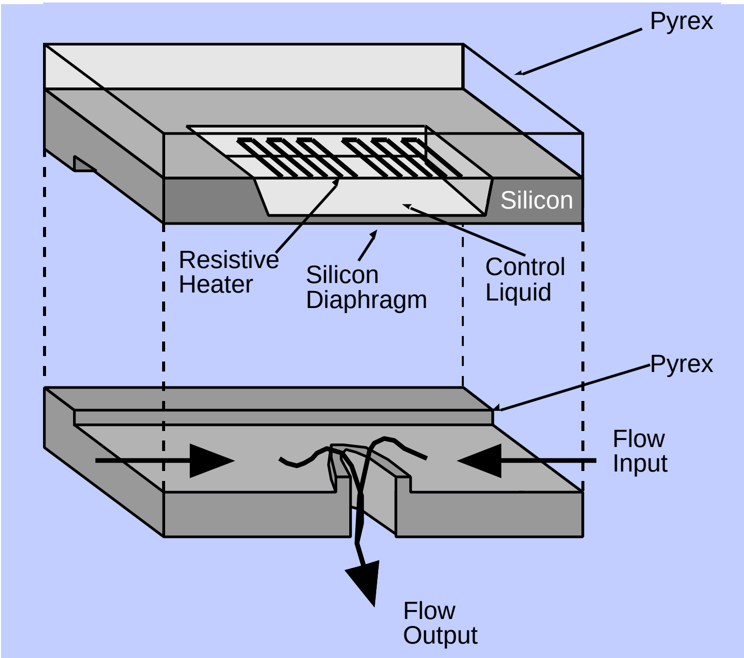
THERMOPNEUMATIC VALVES

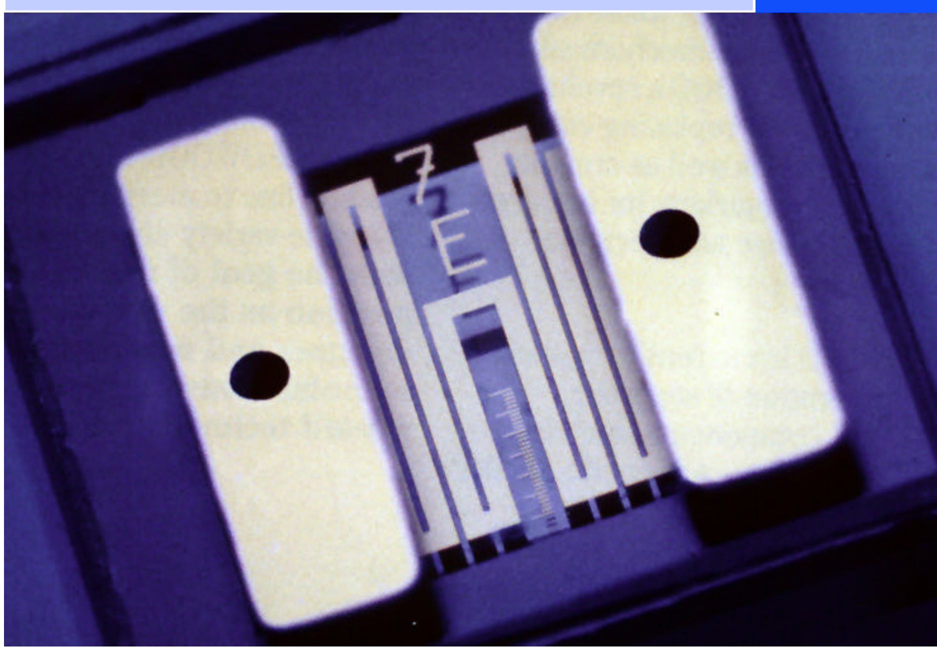


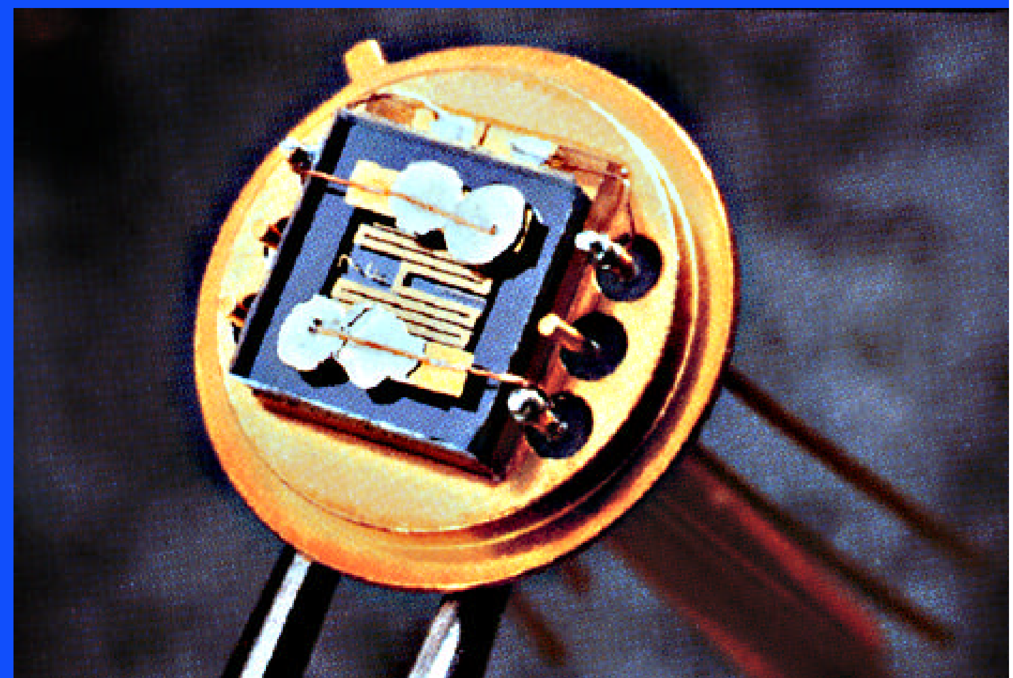
- **Power consumption is approximately 2W.**
- **By appropriate choice of working fluid ("control liquid" in figure), commercial temperature range can be achieved.**
- **Typical membrane excursion is ≈ 50 µm.**

Reference: Zdeblick, M. J., and Angell, J. B., "A Microminiature Electric-to-Fluidic Valve," Proceedings of Transducers '87, the 4th International Conference on Solid-State Transducers and Actuators, Tokyo, Japan, June 2 - 6, 1987, pp. 827 - 829.

THERMOPNEUMATIC VALVE

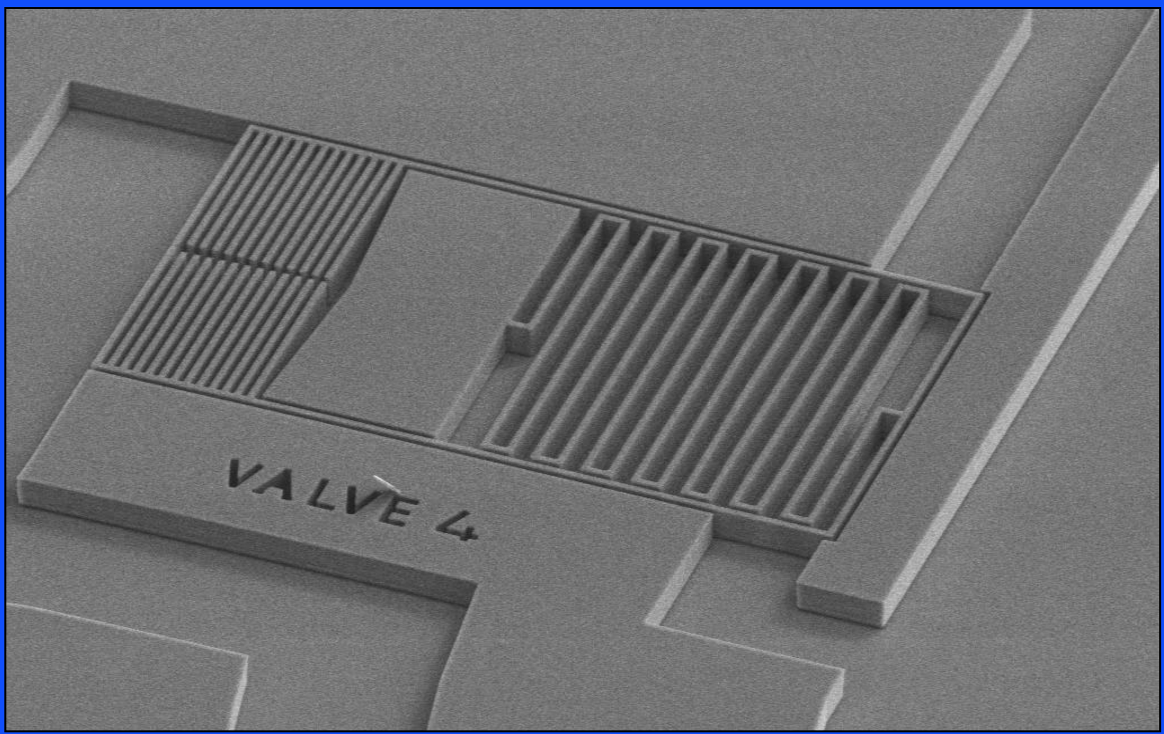






Images courtesy Dr. M. Zdeblick, Redwood Microsystems, Inc.

BUBBLE-ACTUATED VALVE



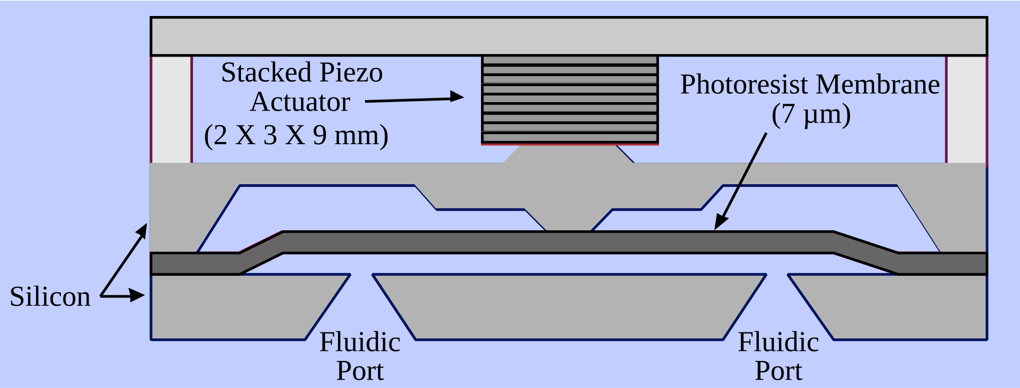
• Flow in the channel on the right is regulated by a mechanical spring structure, shown here in the closed state.

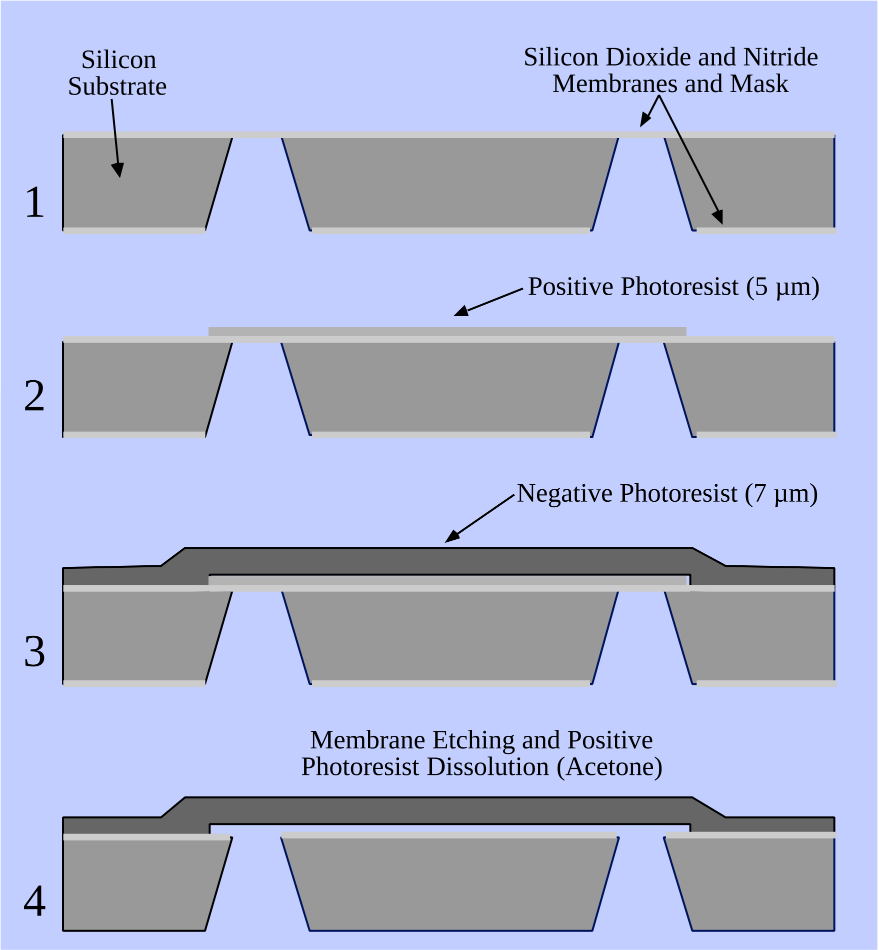
• Inflation of a bubble between the central fixed block and the fin structures on the left causes the fins to move to the left, pulling on rails, which in turn open the valve and compress the spring.

• To close the valve, a bubble escape path is created which allows the bubble to escape from between the central block and the fins, and into the dump channel shown at far left. As the bubble escapes, the spring closes the valve.

Courtesy Dr. J. Evans. Reference: Evans, J.; Liepmann, D.; "The Bubble Spring and Channel (BSaC) Valve: An Actuated, Bi-stable Mechanical Valve for In-Plane Fluid Control", Transducers '99 (The 10th International Conference on Solid-State Sensors and Actuators). Sendai, Japan, June 7-10, 1999, p. 1122-1125.

PIEZOELECTRIC VALVE WITH ORGANIC MEMBRANE

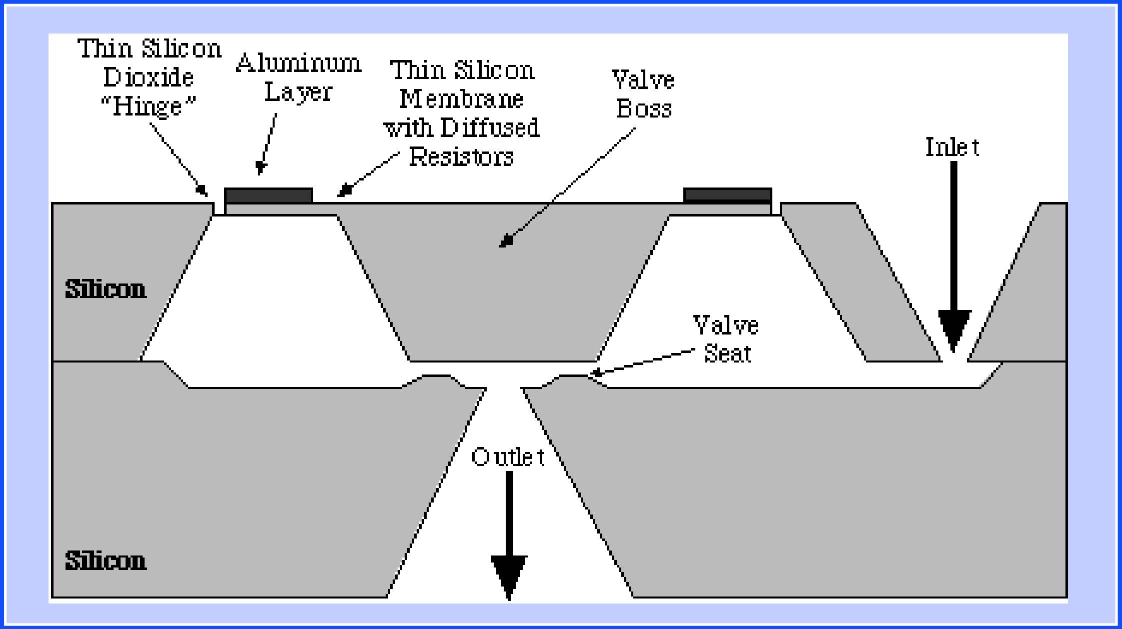


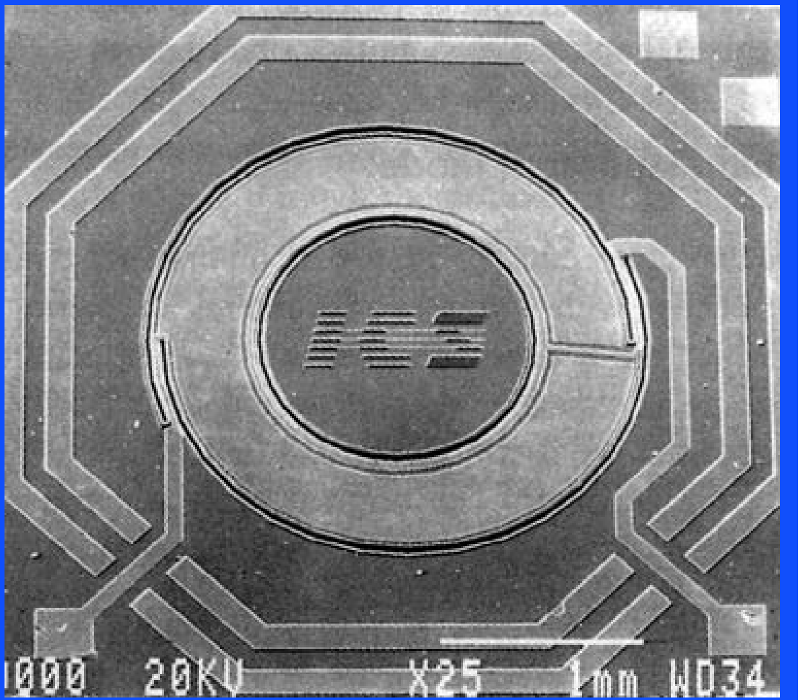


- **Noteworthy in this design is the use of differential photoresist dissolution.**
- **This valve design required up to 100V to operate external piezoelectric actuator stack.**
- **Shoji, et al. (1991) achieved flow rates up to 12 µl/min and could operate at inlet pressures up to 0.5 atm.**

Reference: Shoji, S., van der Schoot, B., de Rooij, N., and Esashi, M., "Smallest Dead Volume Microvalves for Integrated Chemical Analyzing Systems," Proceedings of Transducers '91, the 1991 International Conference on Solid-State Sensors and Actuators, San Francisco, CA, June 24 - 27, 1991, pp. 1052 - 1055.

THERMALLY-DRIVEN VALVES

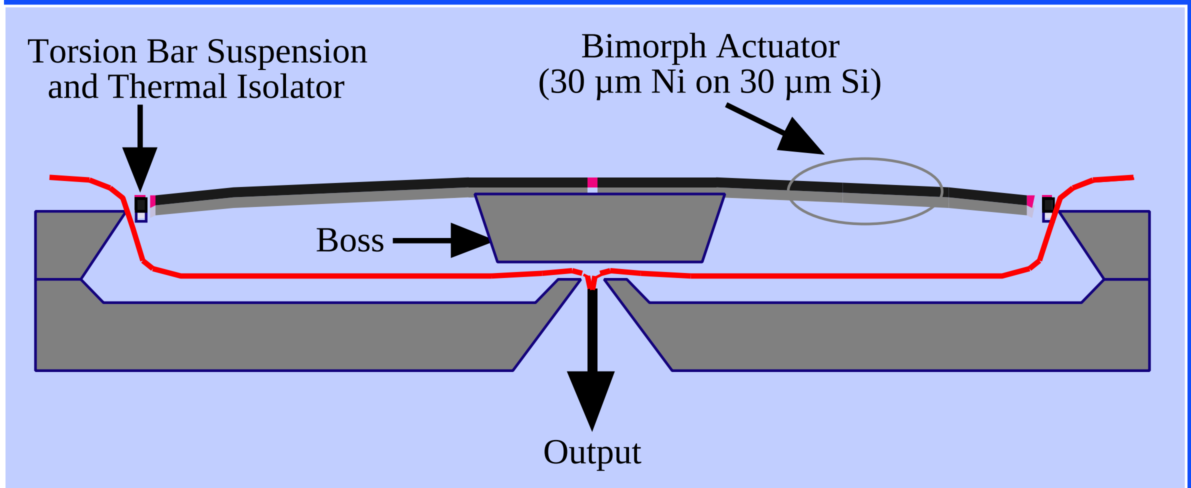


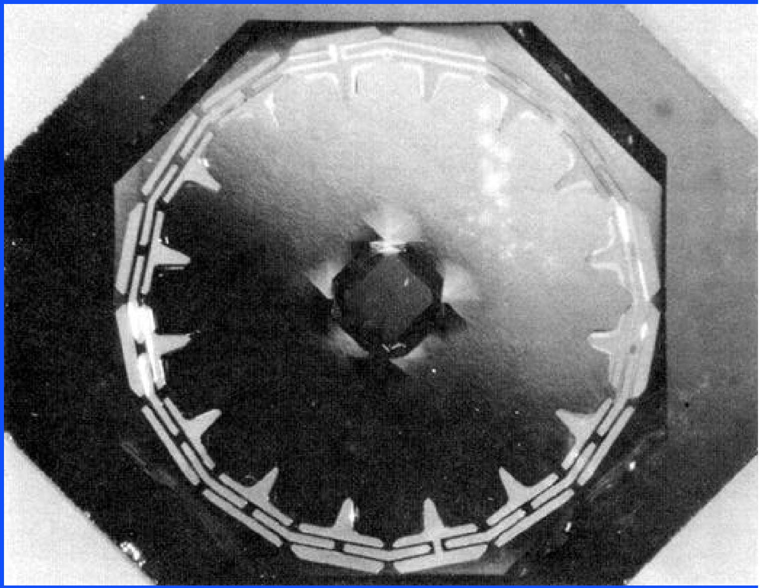


- Normally closed gas valve of Jerman (1991), showing two-wafer construction and thermal bimorph actuation scheme (note that the valve is shown partly open).
- On/off flow ratios (defining leakage) of 5000:1 were achieved, with gas flows of 0 - 150 cc/min possible at inlet pressures of 1 - 50 PSIG, with an input power of 150 mW required for any appreciable flow and more power required for higher flow rates (on the order of 500 mW for full flow).

Source: Jerman, H., "Electrically-Activated, Normally-Closed Diaphragm Valve," Proceedings of Transducers '91, the 1991 International Conference on Solid-State Sensors and Actuators, San Francisco, CA, June 24 - 27, 1991, pp. 1045 - 1048.

BIMORPH ACTUATED GAS VALVE

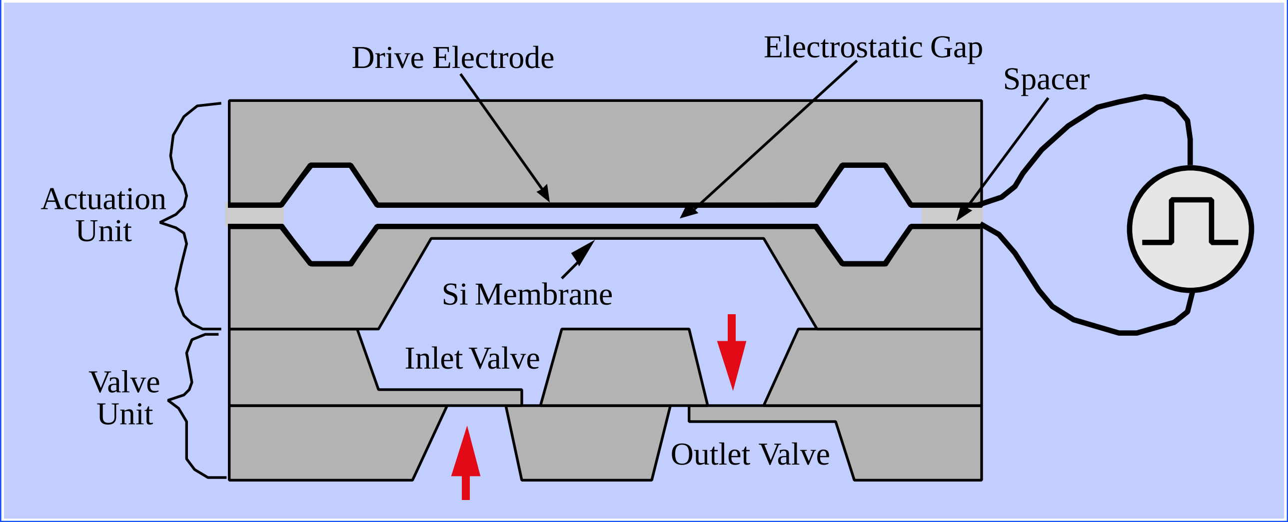




- The design of Barth, et al. (1994) used electroplated Ni (30 µm) on Si bimorphs for actuation.
- Approximately 1W was required for full flow with this normally closed gas valve, which operated over a pressure range of 0 - 200 psi and flow rates of 0 - 600 sccm.

Source: Barth, P. W., Beatty, C. C., Field, L. A, Baker, J. W., and Gordon, G. B., "A Robust, Normally-Closed Silicon Microvalve," Technical Digest, Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 248 - 250.

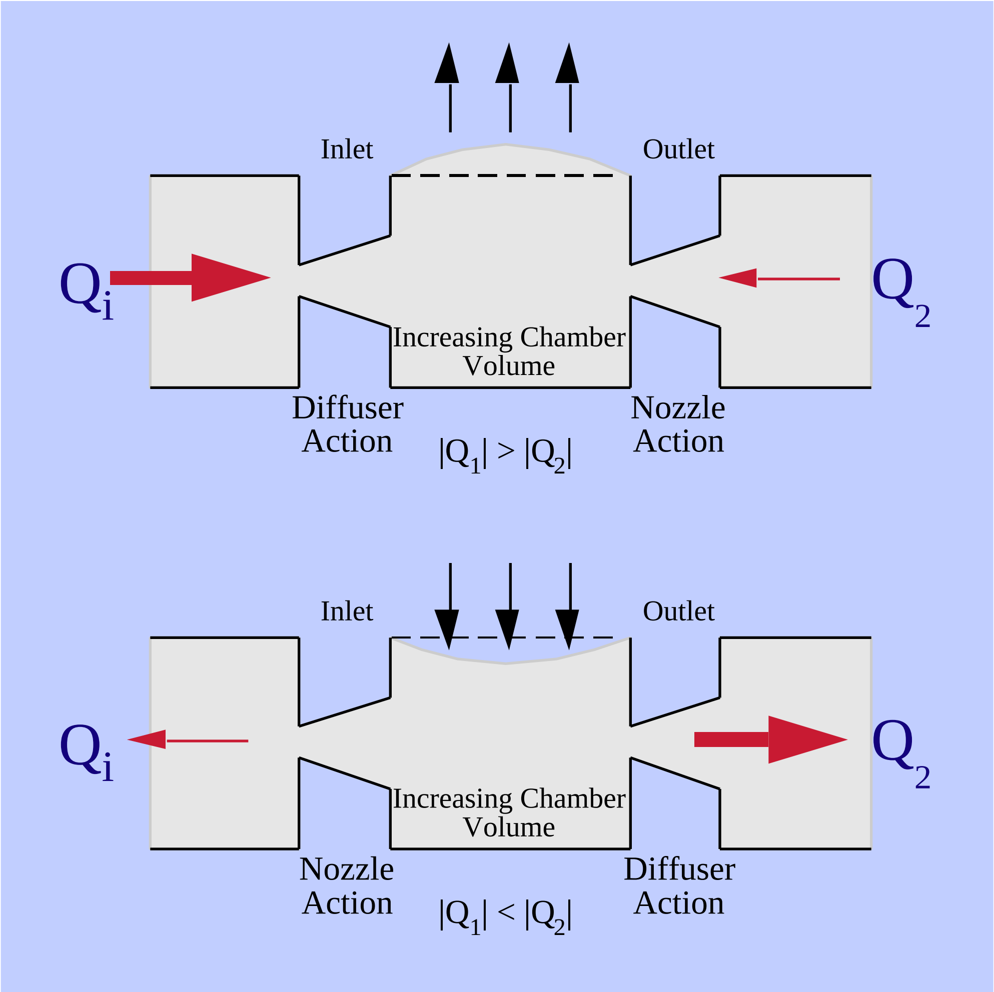
MEMBRANE PUMPS



- **Zengerle, et al. (1995) demonstrated an electrostatically actuated bidirectional membrane pump.**
- **Pulses of 150 - 200 V were used to drive the pump at frequencies of 0.1 Hz - 10 kHz.**
- **At frequencies < 800Hz, the pump operates in the forward mode, and at frequencies from 2 - 8 kHz, it reverses (due to phase shift between response of valves and pressure pulses.**
- **Flow rates were 250 - 850 µl/min (forward) and 200 - 350 µl/min (reverse).**

Reference: Zengerle, R., Kluge, S., Richter, M., and Richter, A., "A Bidirectional Silicon Micropump," Proceedings of the IEEE 1995 Micro Electro Mechanical Systems Workshop (MEMS '95), Amsterdam, Netherlands, Jan. 29 - Feb. 2, 1995, IEEE, pp. 19 - 24.

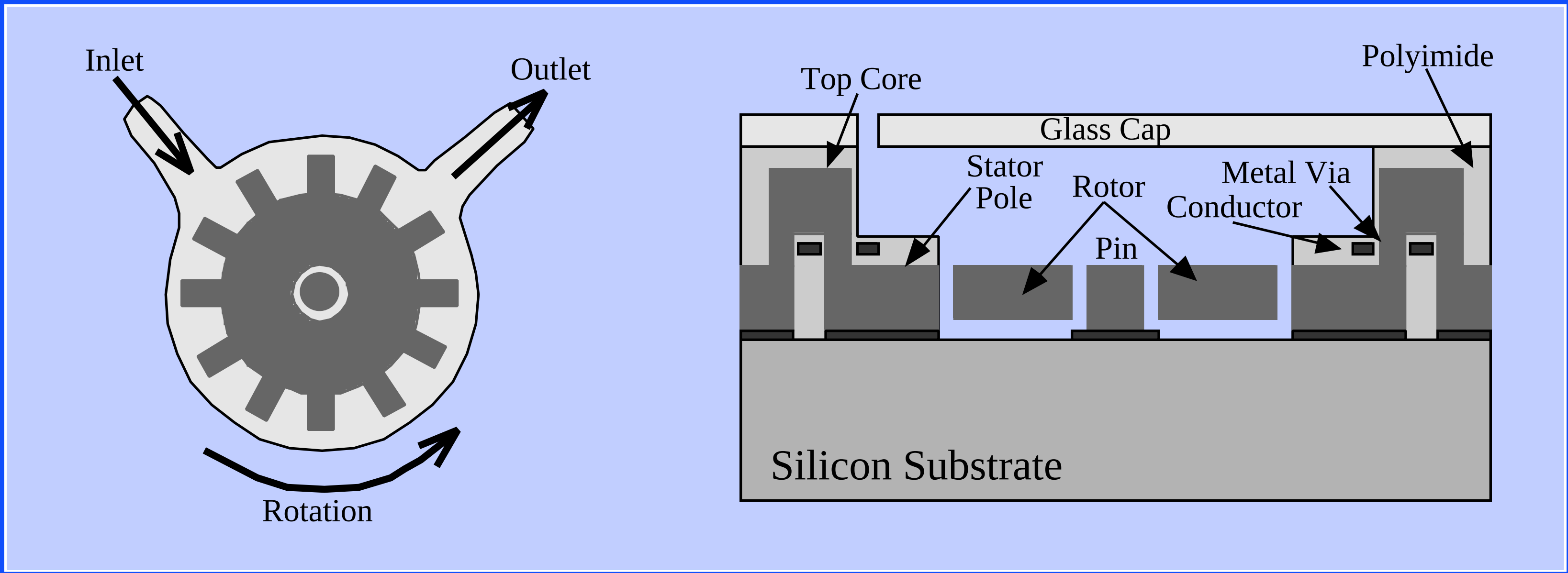
DIFFUSER PUMPS



- **Kinetic energy (flow velocity) of the fluid is transformed into potential energy (pressure) in the pump ("pressure recovery"), but the efficiency of this process is greater in the diffuser direction than in the nozzle direction.**
- **Ports conduct more fluid in the diffuser direction than the nozzle direction, resulting in a net pumping action (this effect is sometimes referred to as "flow rectification").**

Reference: Stemme, E., and Stemme, G., "Valveless Diffuser/Nozzle-Based Fluid Pump," Sensors and Actuators, vol. A39, no. 2, Nov. 1993. pp. 159 - 167.

ROTARY PUMPS



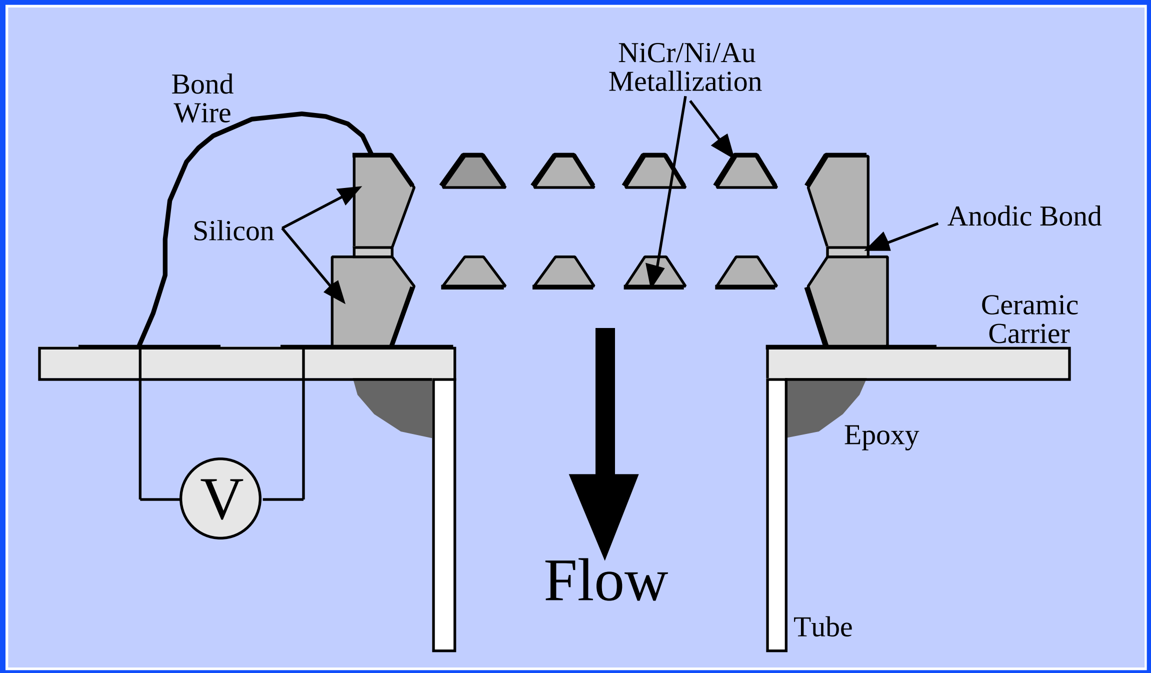
- **Photosensitive polyimide template plating of permalloy (81% Ni, 19% Fe) was used to fabricated the rotor and stator poles, with multi-level plating used to fabricate monolithic stator coils.**
- **At 0.6 - 1.5W, flows of 24 µl/min were demonstrated at 5000 rpm with an achievable differential pressure of 100 hPa.**

Reference: Ahn, C. H., and Allen, M. G., "Fluid Micropumps Based on Rotary Magnetic Actuators," Proceedings of the 1995 IEEE Micro Electro Mechanical Systems Workshop (MEMS '95), Amsterdam, Netherlands, Jan. 29 - Feb. 2, 1995, pp. 408 - 412.

ELECTROHYDRODYNAMIC (EHD) PUMPS

- *Injection-type* EHD pumps rely on the fact that controllable concentrations of ions can be created from dielectric liquids at voltages above ≈ 100 kV/cm (corresponds to 10 V/µm) at which point even insulating fluids can support current flows.
- The current flowing under those conditions consists of homocharges (same polarity as the generating electrode) that arise through electrochemical reactions there -> the injected charges can then be acted upon by an electric field to pump the fluid.
- *Non-injection type* EHD pumps rely on obtaining conductivity or permittivity gradients (through temperature gradients or layering of materials) and applying traveling wave potentials to pump the fluid.
- Neither type can generate large pressure heads.

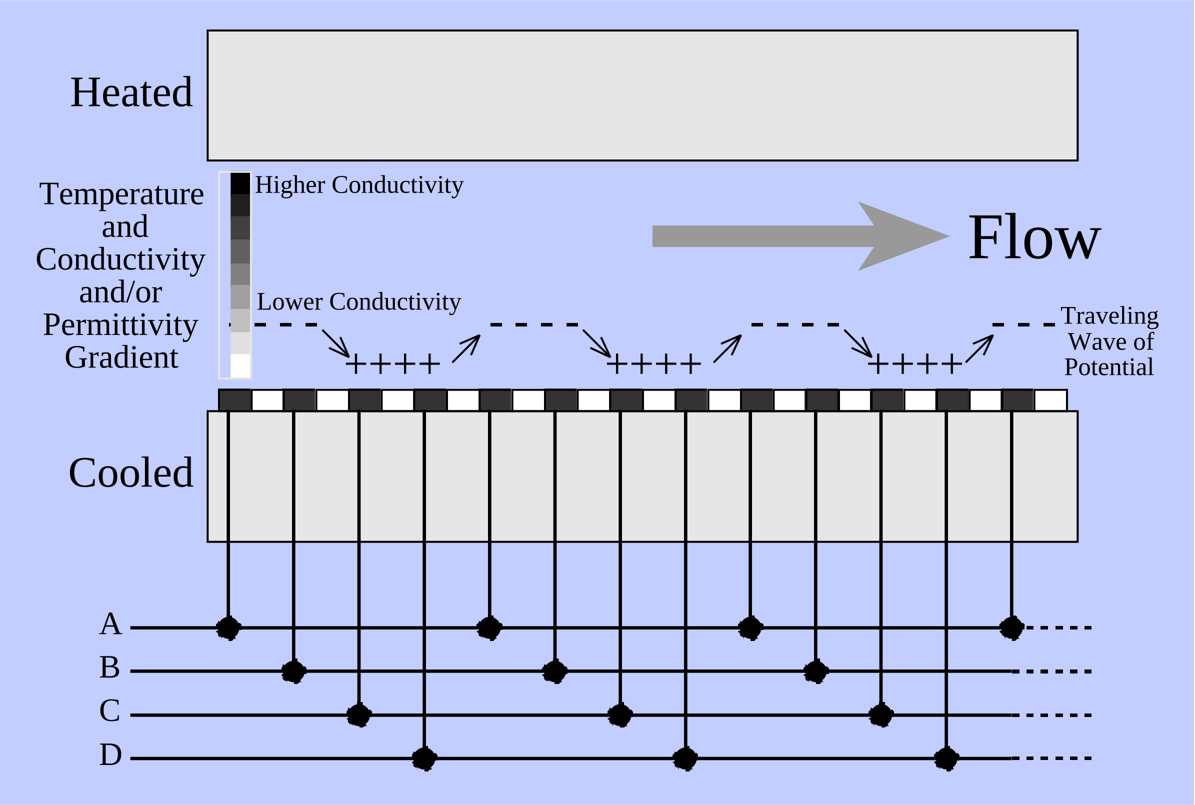
INJECTION-TYPE EHD PUMP



- With this design, ethanol, methanol, propanol and acetone could be pumped, as could deionized water, although electrolysis (and bubble formation) interfered with pumping.
- At 700 V, a maximum pressure of 2840 Pa was achieved, and in a separate experiment, a maximum flow rate of 14 ml/min was achieved at a pressure of 420 Pa.

Reference: Richter, A., Plettner, A., Hofmann, K. A., and Sandmaier, H., "A Micromachined Electrohydrodynamic (EHD) Pump," Sensors and Actuators, vol. A29, no. 2, Nov. 1991, pp. 159 - 168.

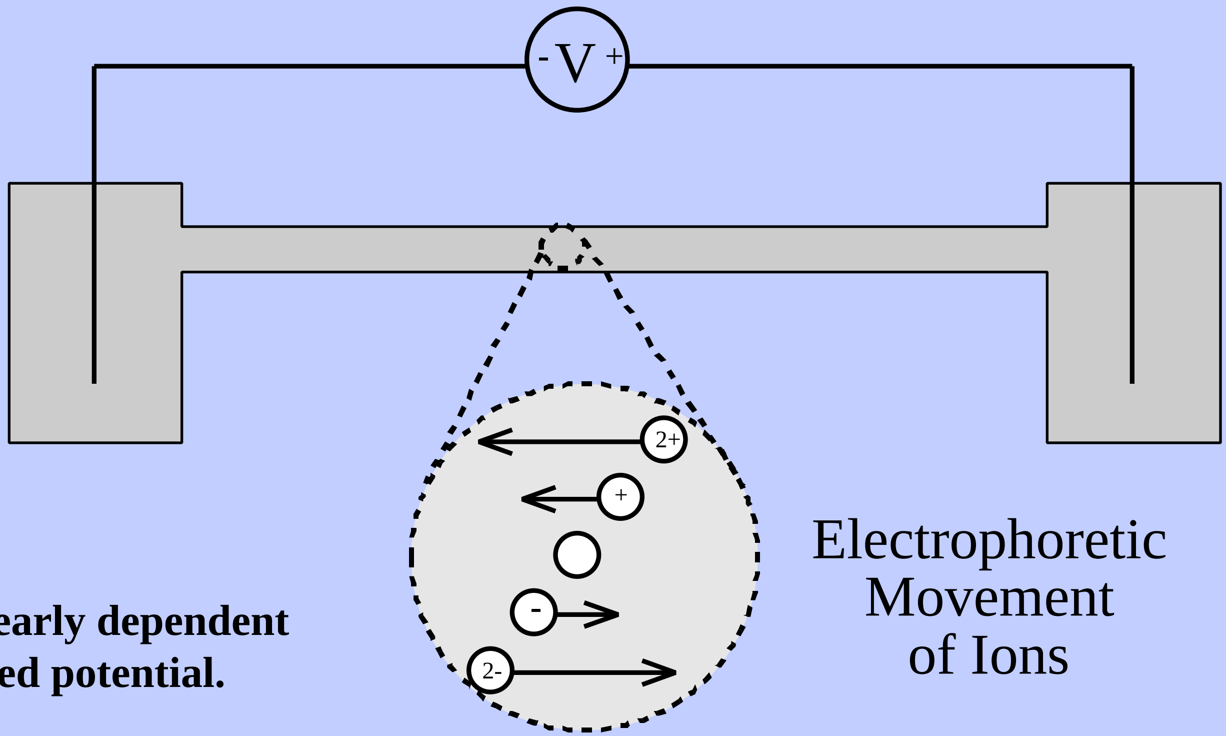
NON-INJECTION EHD PUMP



- **Fuhr, et al. (1994) demonstrated micromachined EHD pumps based on multiple 1 μm thick electroplated gold electrodes on quartz or oxidized silicon wafers, sealed from above using a Plexiglass™ cover with machined fluid transport channel(s).**
- **The streaming velocity of suspended latex particles was found to vary with the applied voltage as $V^{2.5}$, between the minimum voltage at which pumping was seen (10 V) to the maximum that could be applied (40 - 50 V, limited by bubbles from electrolysis).**

Reference: Fuhr, G., Schnelle, T., and Wagner, B., "Travelling Wave-Driven Microfabricated Electrohydrodynamic Pumps for Liquids," Journal of Micromechanics and Microengineering, vol. 4, no. 4, Dec. 1994, pp. 217 - 226.

ELECTROPHORESIS

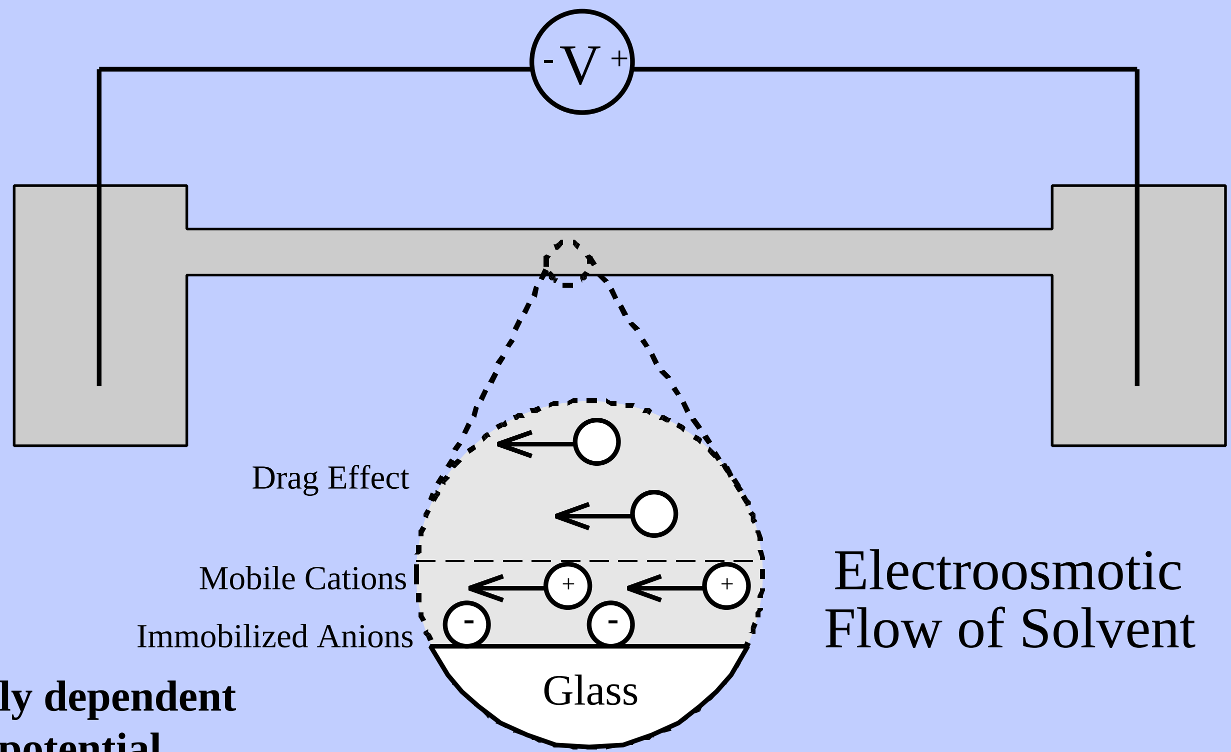


Electrophoretic Movement of Ions

Rate linearly dependent on applied potential.

Reference: Manz, A., Effenhauser, C. S., Burggraf, N., Harrison, D. J., Seiler, K., and Flurri, K., "Electroosmotic Pumping and Electrophoretic Separations for Miniaturized Chemical Analysis Systems," Journal of Micromechanics and Microengineering, vol. 4, 1994, pp. 257 - 265.

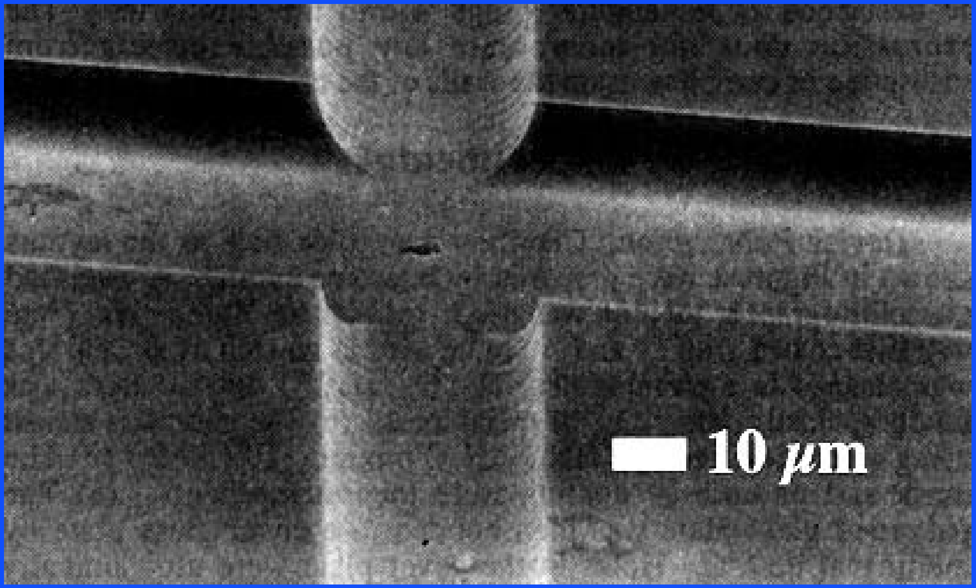
ELECTROOSMOSIS

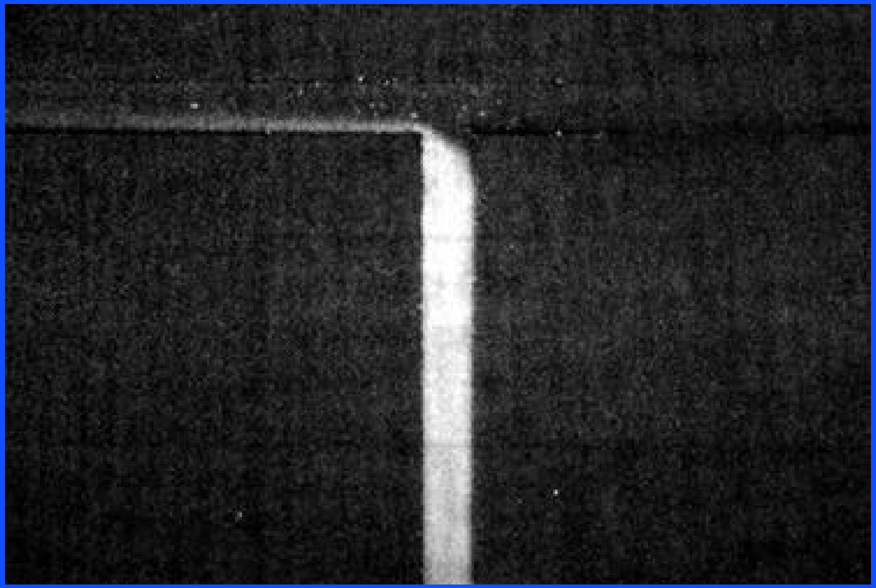


Rate linearly dependent on applied potential.

Electrically neutral fluids can be pumped due to drift of mobile ions forming a double-layer near fixed surface charges. Solvent is osmotically "dragged" along.

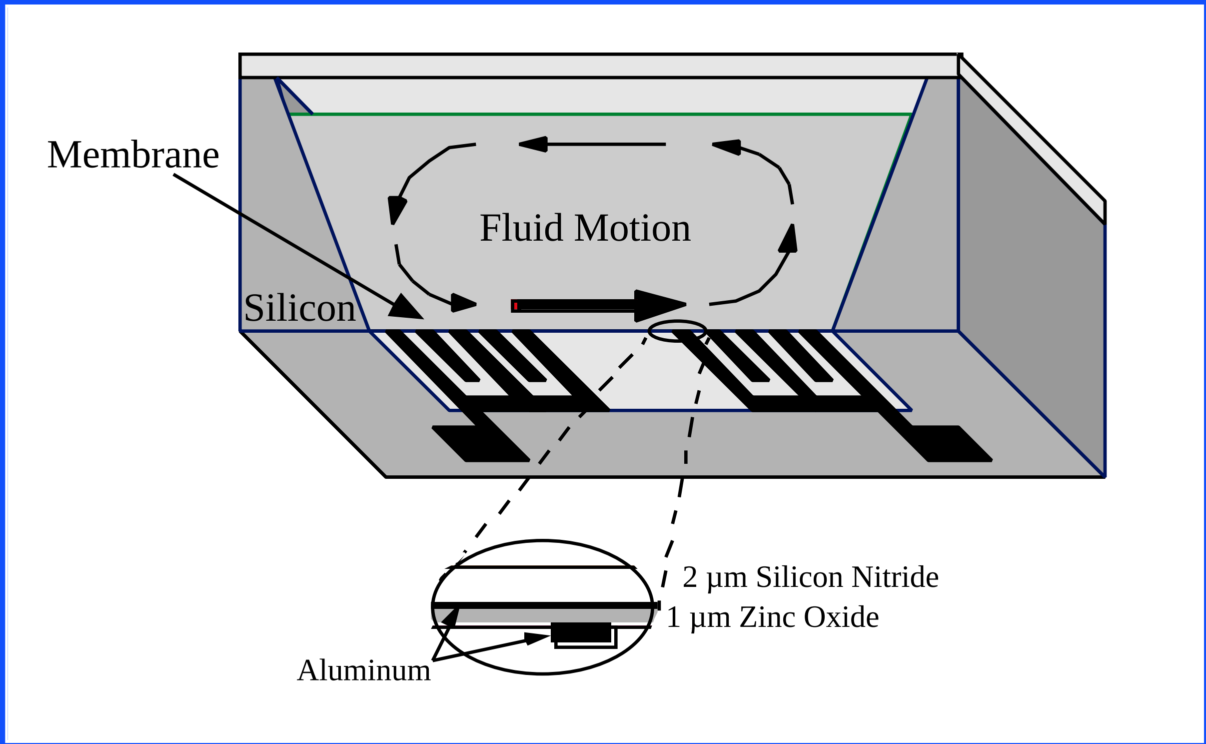
Reference: Manz, A., Effenhauser, C. S., Burggraf, N., Harrison, D. J., Seiler, K., and Flurri, K., "Electroosmotic Pumping and Electrophoretic Separations for Miniaturized Chemical Analysis Systems," Journal of Micromechanics and Microengineering, vol. 4, 1994, pp. 257 - 265.





Source: Harrison, D. J., Fluri, K., Fan, Z., and Seiler, K., "Integration of Analytical Systems Incorporating Chemical Reactions and Electrophoretic Separation," Micro Total Analysis Systems, Proceedings of μTAS '94 Workshop, Twente, Netherlands, Nov. 21 - 22, 1994 pp. 105 - 115.

ULTRASONIC PUMPS



Reference: Moroney, R. M., White, R. M., and Howe, R. T., "Ultrasonically Induced Microtransport," Proceedings of the IEEE 1991 Micro Electro Mechanical Systems Workshop (MEMS '91), Nara, Japan, Jan. 30 - Feb. 2, 1991, pp. 277 - 282.

DROPLET GENERATORS

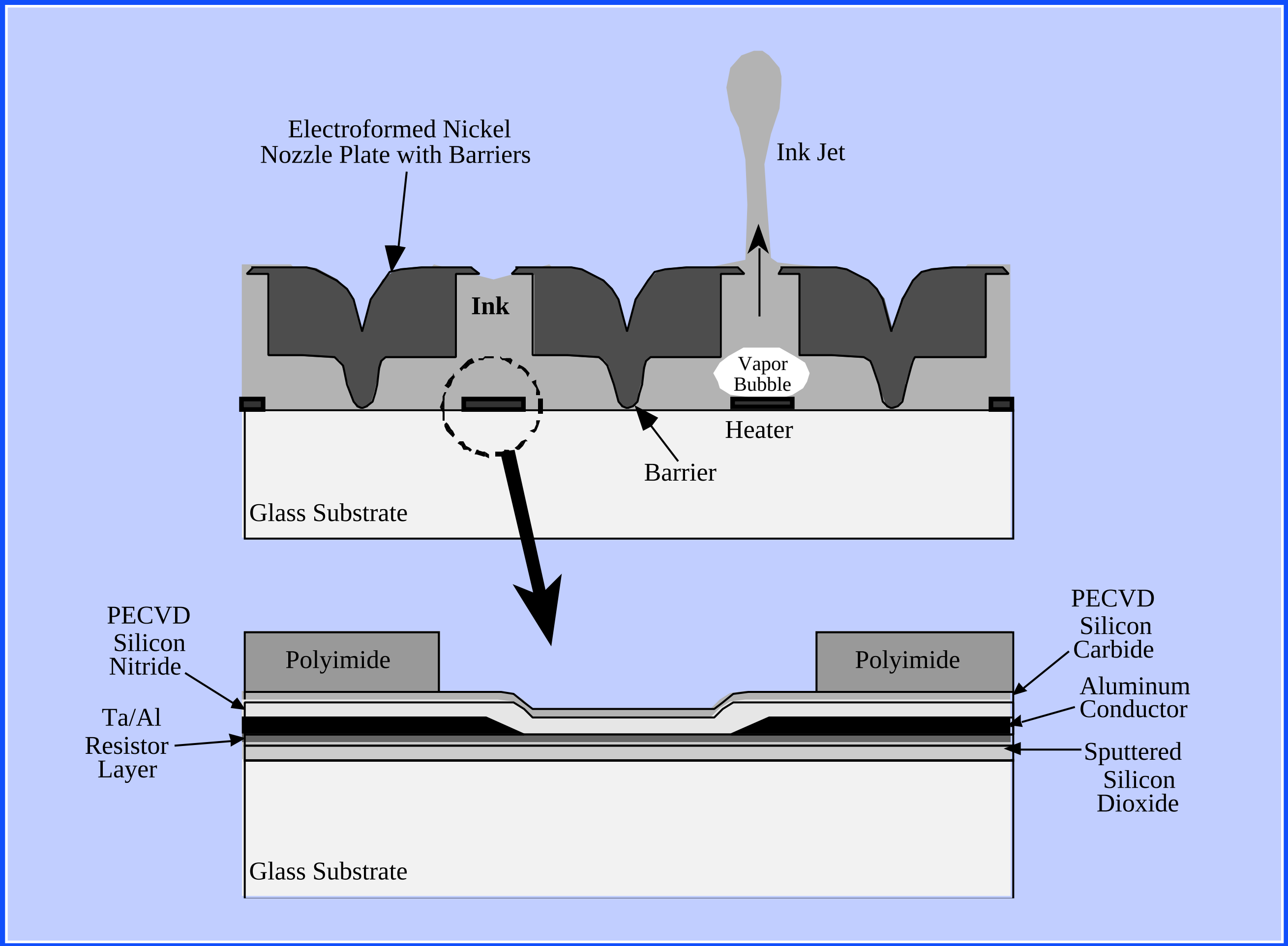
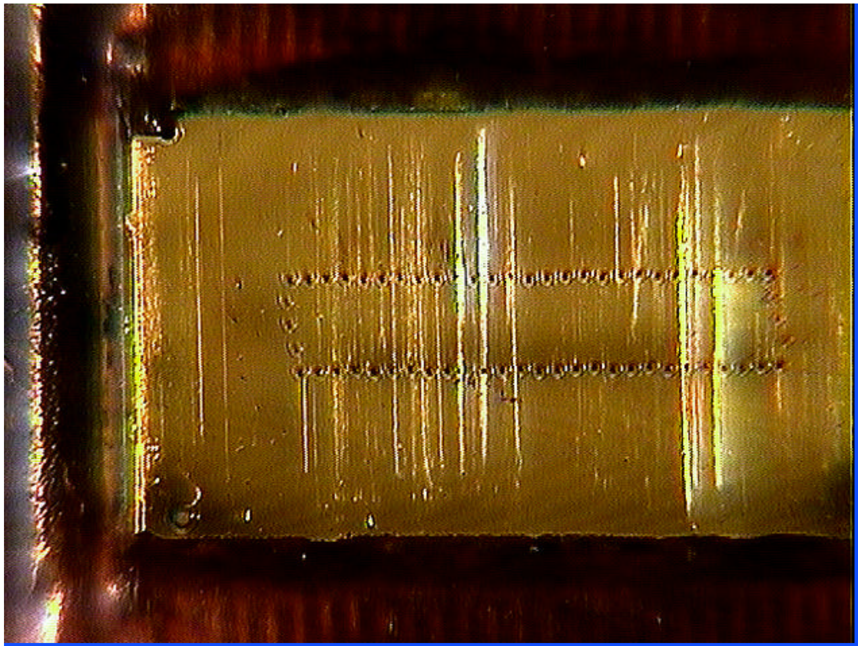
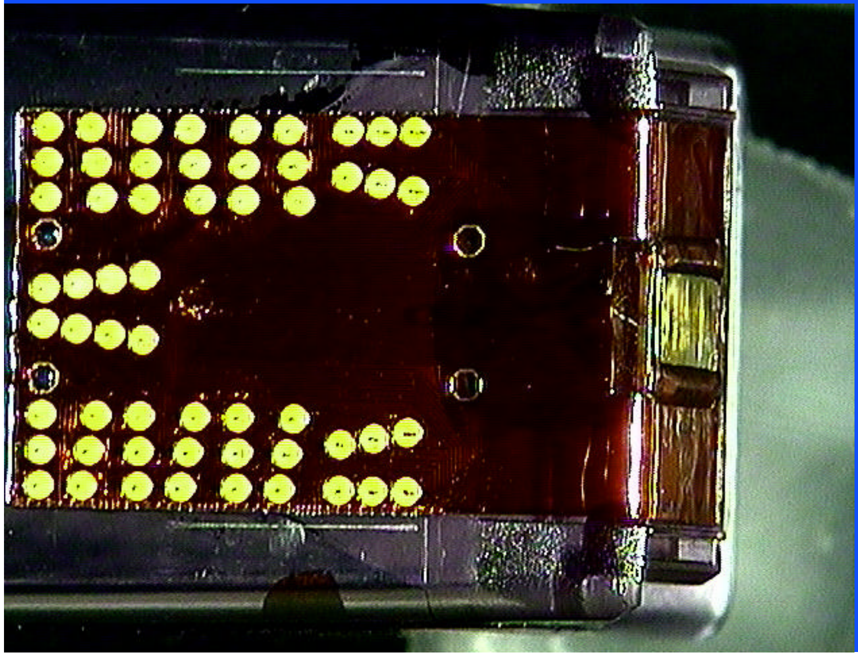


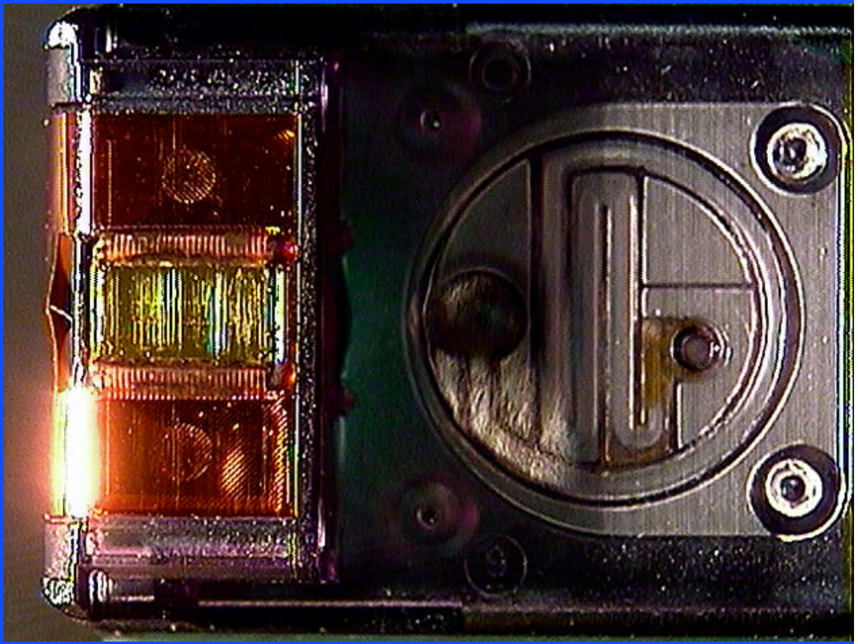
Illustration of Hewlett-Packard ink jet devices, showing bonded electroformed nickel nozzle plate and multilayer thin-film heaters.

Reference: Allen, R. R., Meyer, J. D., and Knight, W. R., "Thermodynamics and Hydrodynamics of Thermal Ink Jets," Hewlett-Packard Journal, vol. 36, no. 5, May 1985, pp. 21 - 27.

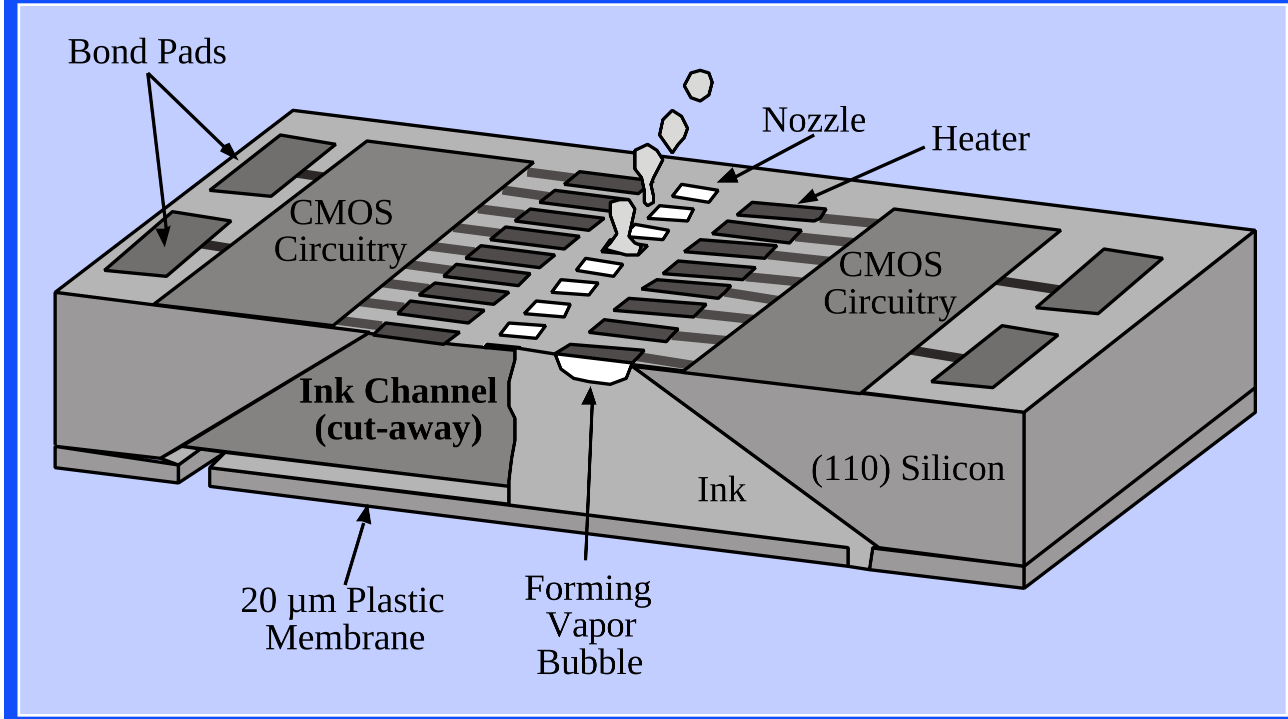


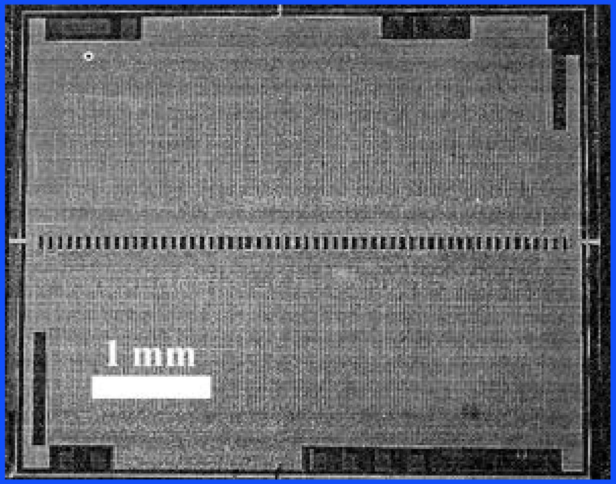


HP INKJET CARTRIDGE

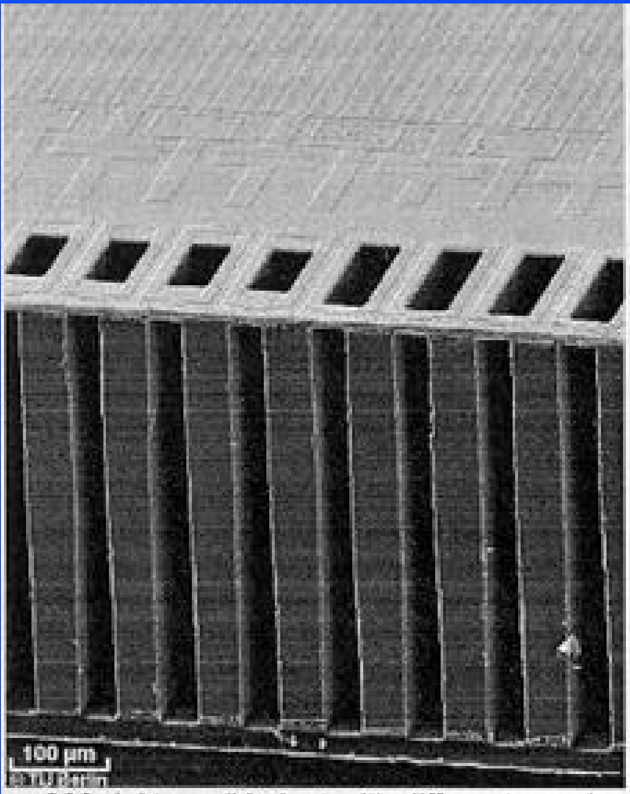


CMOS INTEGRATED INKJET

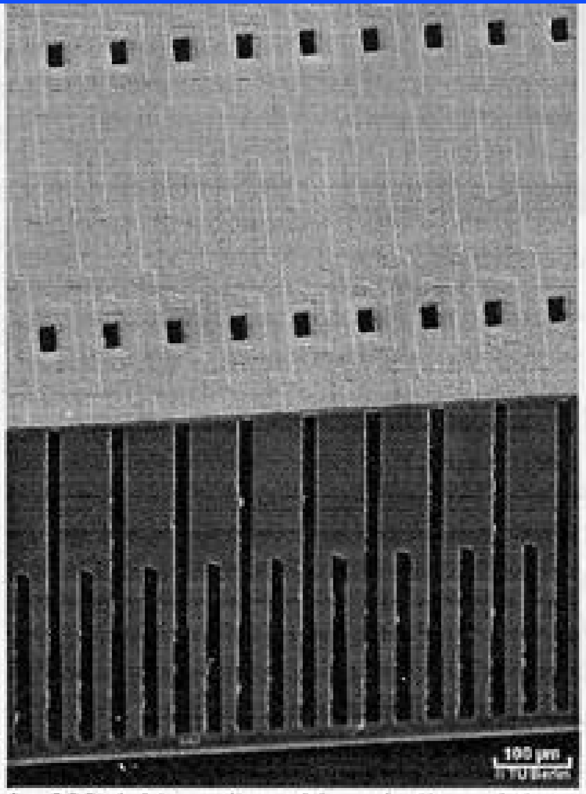




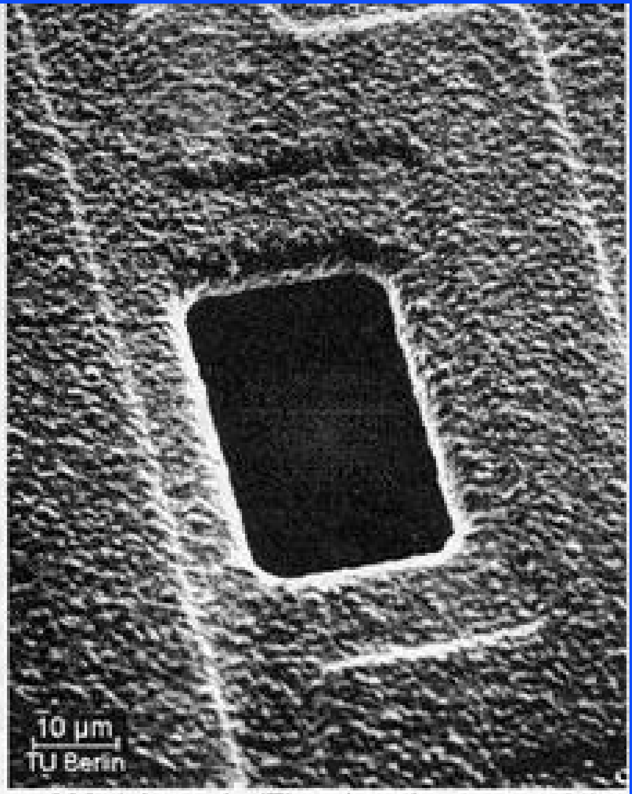
Source: Krause, P., Obermeier, E., and Wehl, W., "Backshooter - A New Smart Micromachined Single-Chip Inkjet Printhead," Proceedings of Transducers '95, the 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX, Stockholm, Sweden, June 25 - 29, 1995, vol. 2, pp. 325 - 328.



a: 300 dpi type (Variant with different nozzle dimensions)



b: 600 dpi type (to achieve better print quality, direct neighbouring channels are shifted)



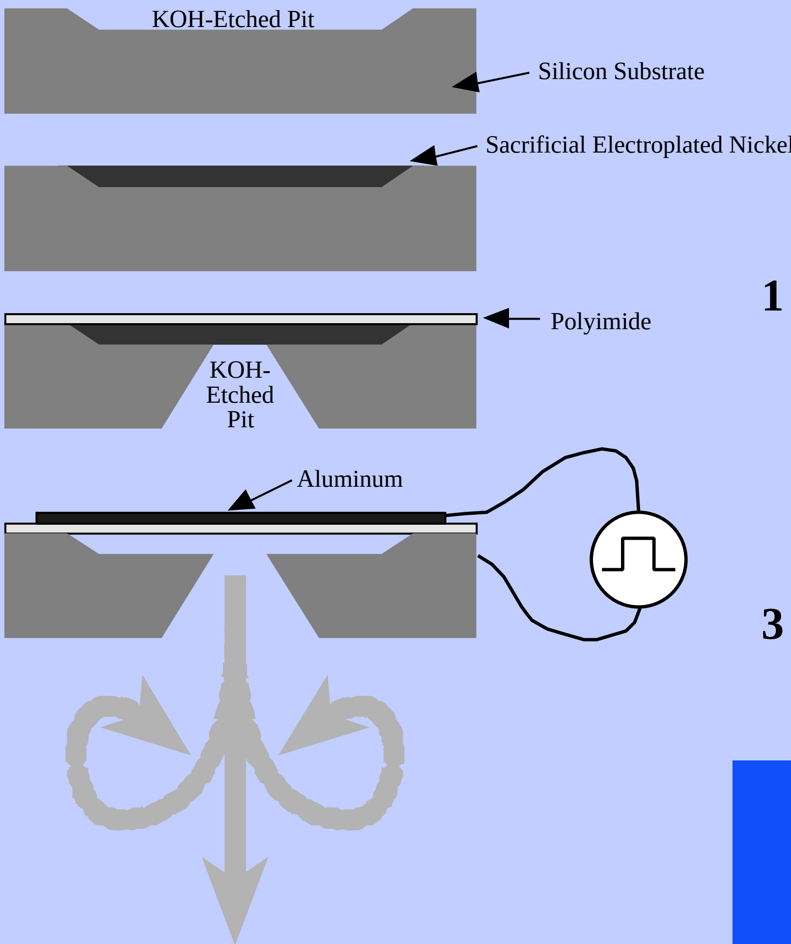
c: 600 dpi nozzle (The elevations around the nozzle are caused by Al-leads)

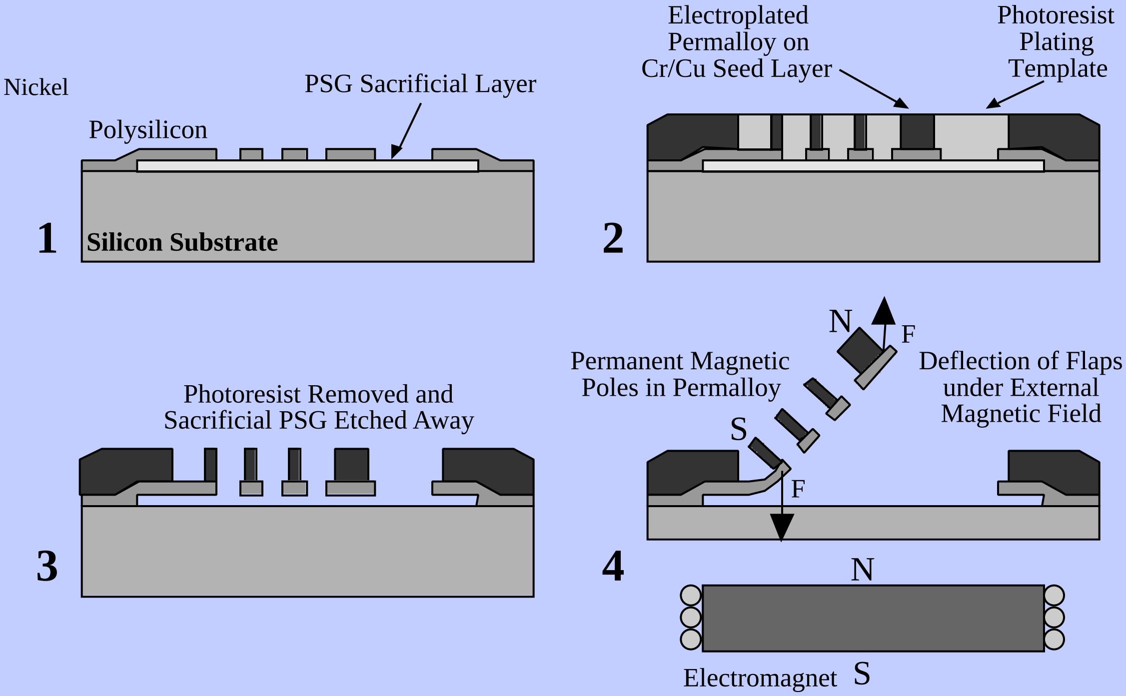
Source: Krause, P., Obermeier, E., and Wehl, W., "Backshooter - A New Smart Micromachined Single-Chip Inkjet Printhead," Proceedings of Transducers '95, the 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX, Stockholm, Sweden, June 25 - 29, 1995, vol. 2, pp. 325 - 328.

SAW AEROSOL GENERATOR

Source: Kurosawa, M., Watanabe, T., and Higuchi, T., "Surface Acoustic Wave Atomizer with Pumping Effect, Proceedings of the IEEE Micro Electro Mechanical Systems Conference, Amsterdam, Netherlands, Jan. 29 - Feb. 2, 1995, IEEE Press, pp. 25 - 30.

CONTROL OF MACROSCOPIC FLOWS

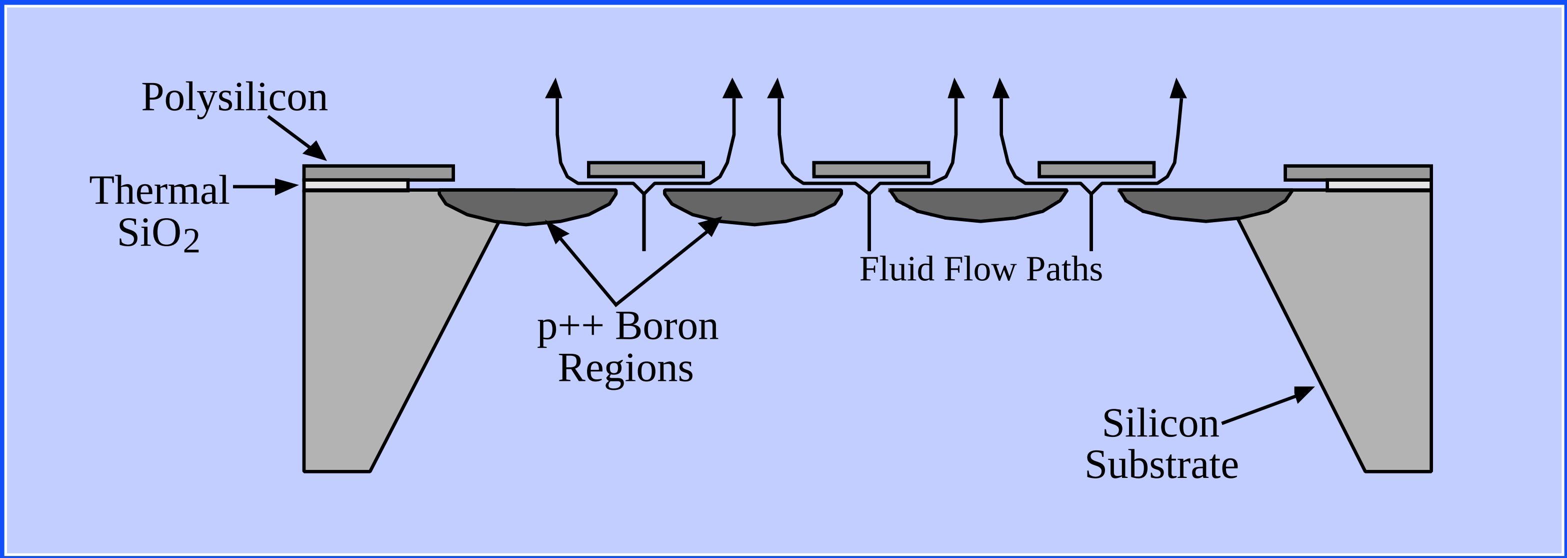




Reference: Liu, C., Tsao, T., Tai, Y.-C., Leu, T.-S., Ho, C.-H., Tang. W.-L., and Miu, D., "Out-of-Plane Permalloy Magnetic Actuators for Delta-Wing Control," Proceedings of the IEEE 1995 Micro Electro Mechanical Systems Workshop (MEMS '95), Amsterdam, Netherlands, Jan. 29 - Feb. 2, 1995, pp. 7 - 12.

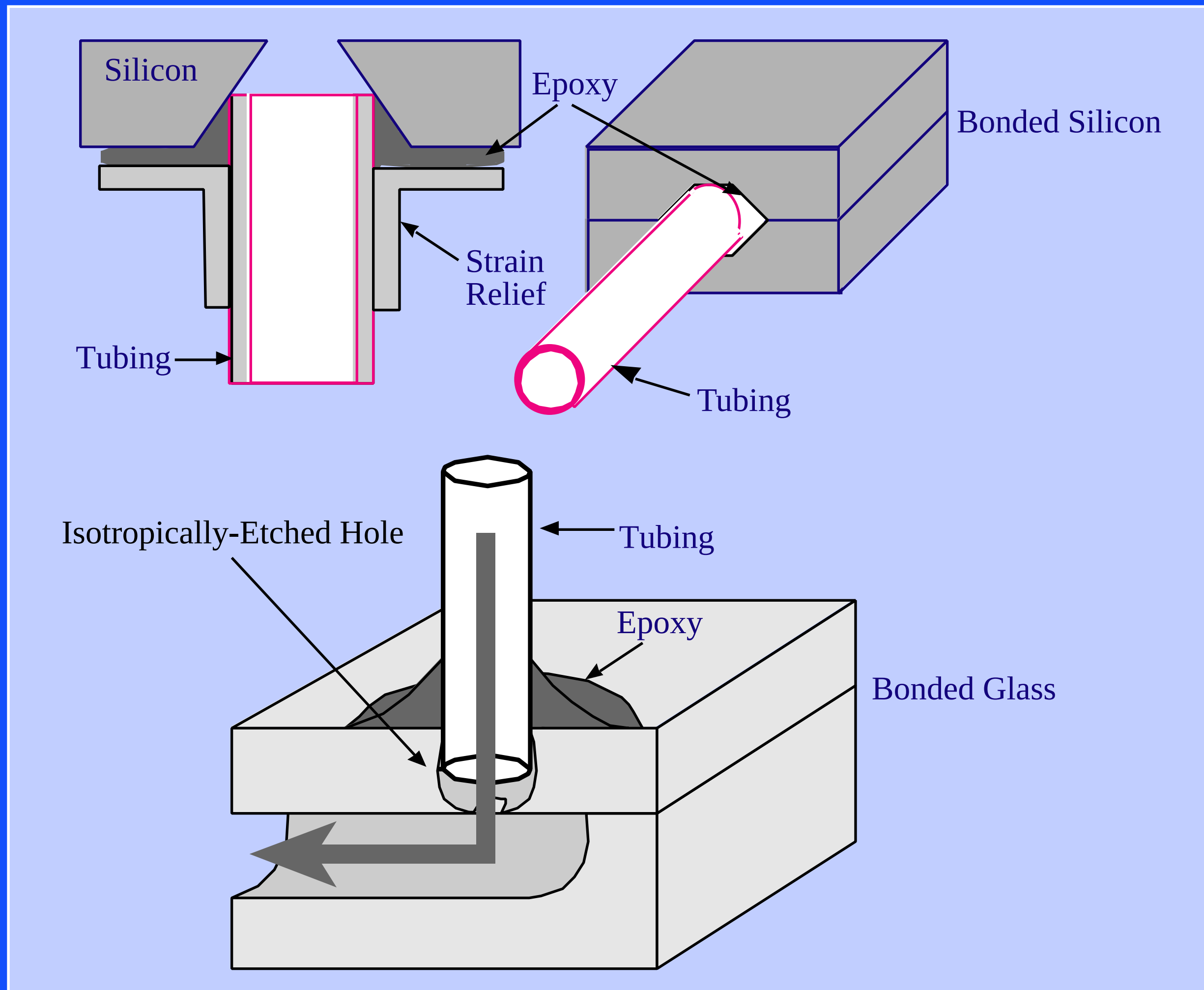
Reference: Coe, D. J., Allen, M. G., Smith, B. L., and Glezer, A., "Addressable Micromachined Jet Arrays," Proceedings of Transducers '95, the 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX, Stockholm, Sweden, June 25 - 29, 1995, vol. 2, pp. 329 - 332.

PARTICLE FILTERS



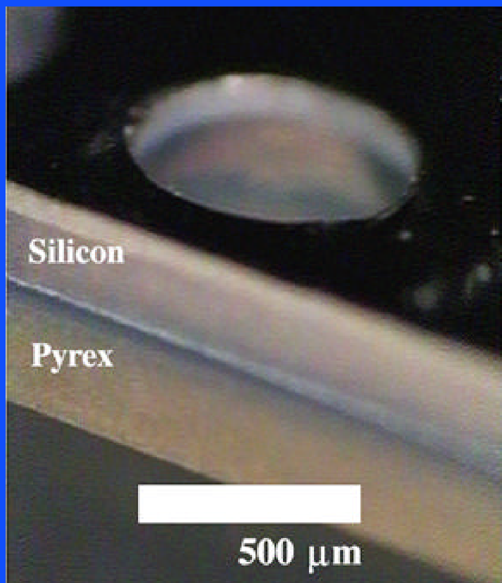
Reference: Kittilsland, G., Stemme, G., and Nordén, B., "A Sub-Micron Particle Filter in Silicon," Sensors and Actuators, vol. A23, nos. 1 - 3, Apr. 1990, pp. 904 - 907.

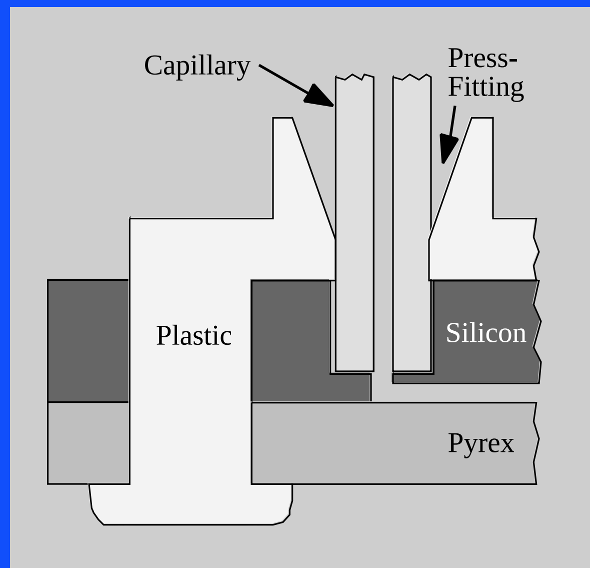
FLUIDIC INTERCONNECTS

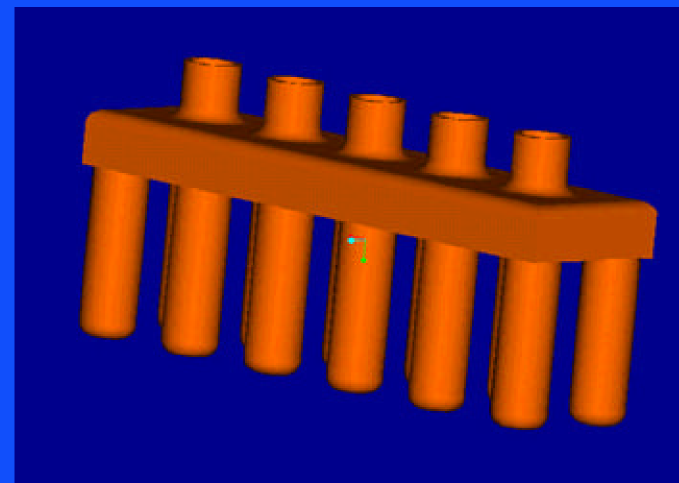


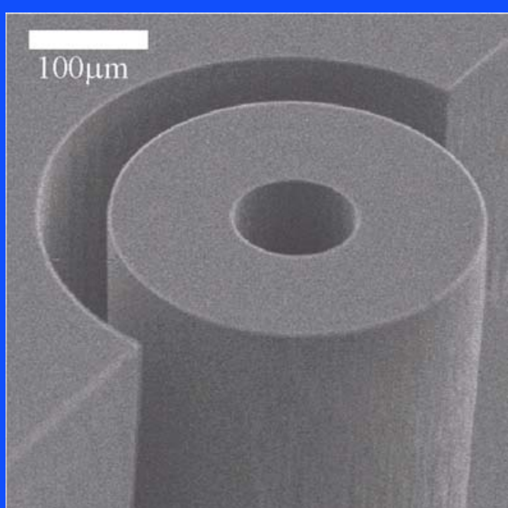
Reference: Krulevitch, P., Microfluidics Section in "MEMS for Medical and Biotechnological Applications," Course Notes, UCLA Extension, Mar. 1995.

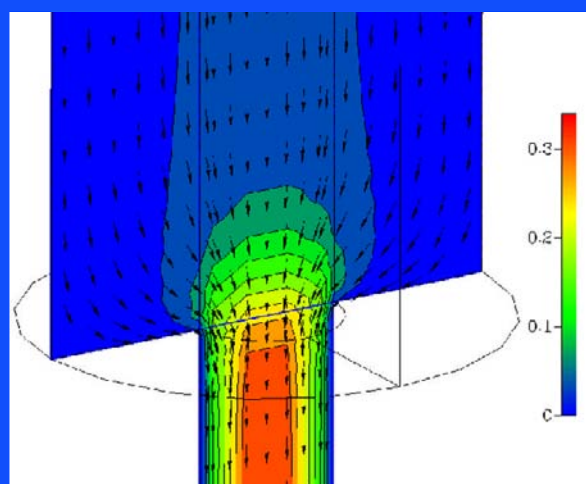
PRECISION FLUIDIC COUPLERS

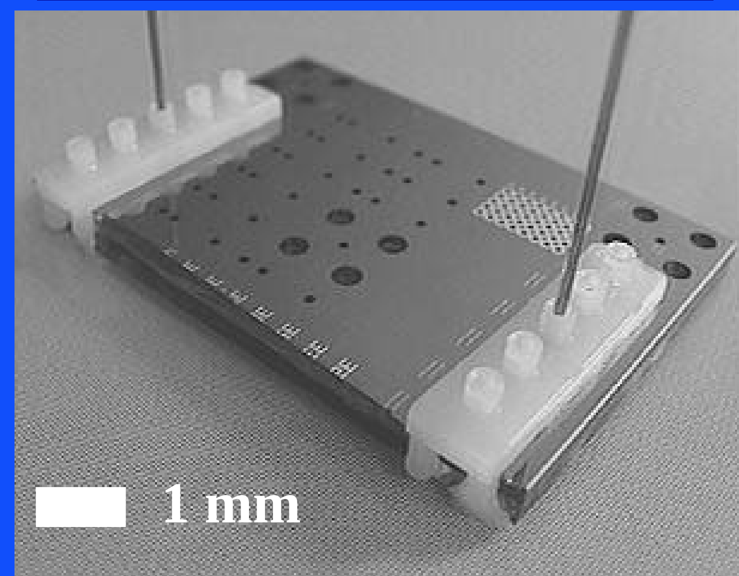






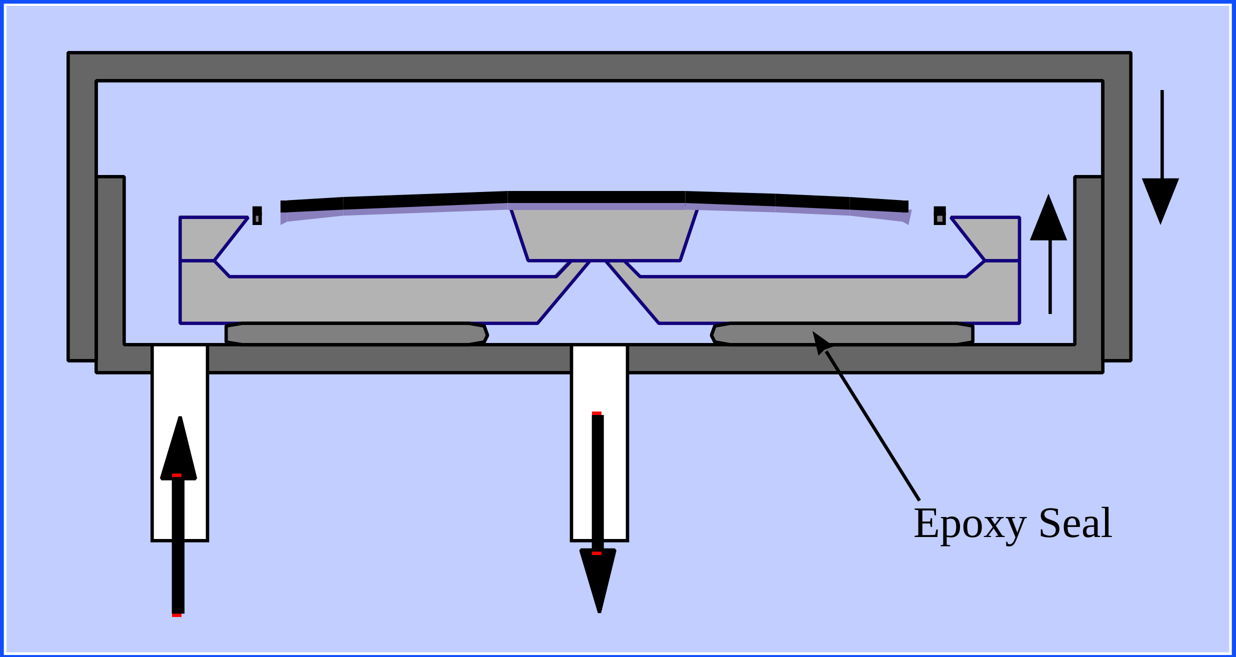






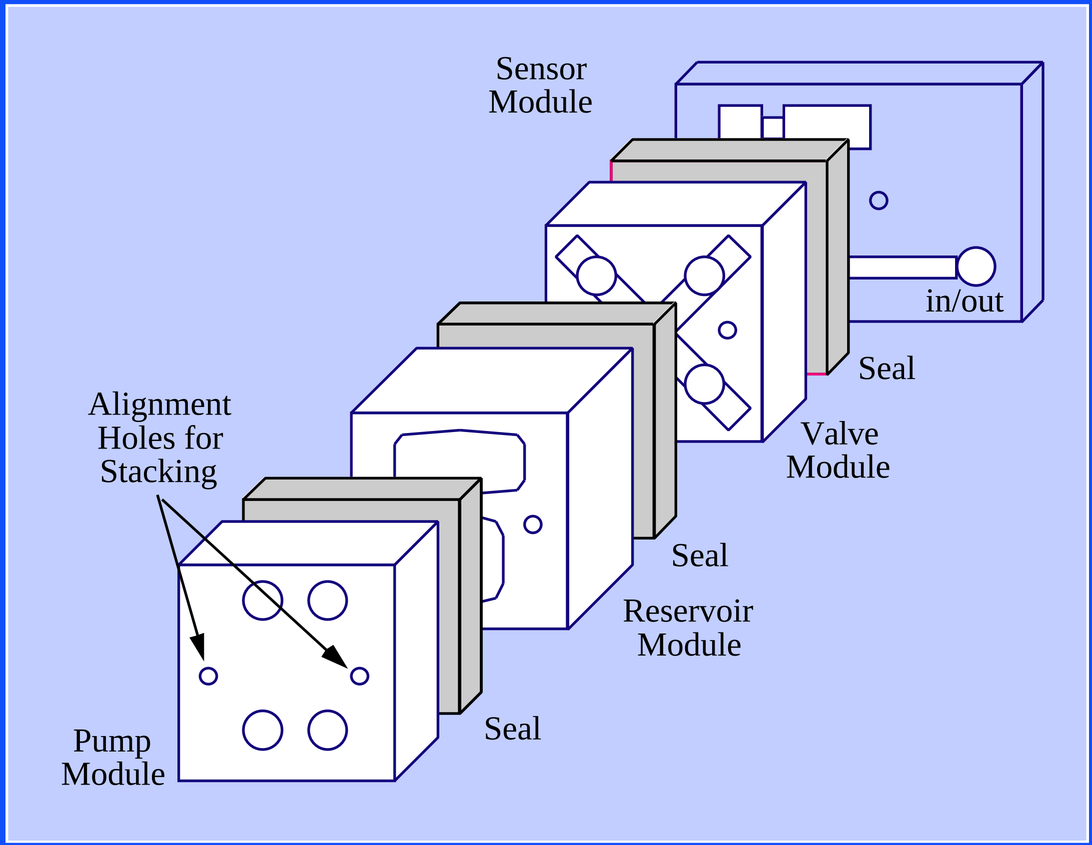
Reference: Gray, B. L., Jaeggi, D., Mourlas, N. J., van Drieënhuizen, B. P., Williams, K. R., Maluf, N. I., and Kovacs, G. T. A., "Novel Interconnection Technologies for Integrated Microfluidic Systems," Sensors and Actuators A, vol. 77, no. 1, Sept. 28, 1999, pp. 57 - 65.

PACKAGING FOR FLUIDICS



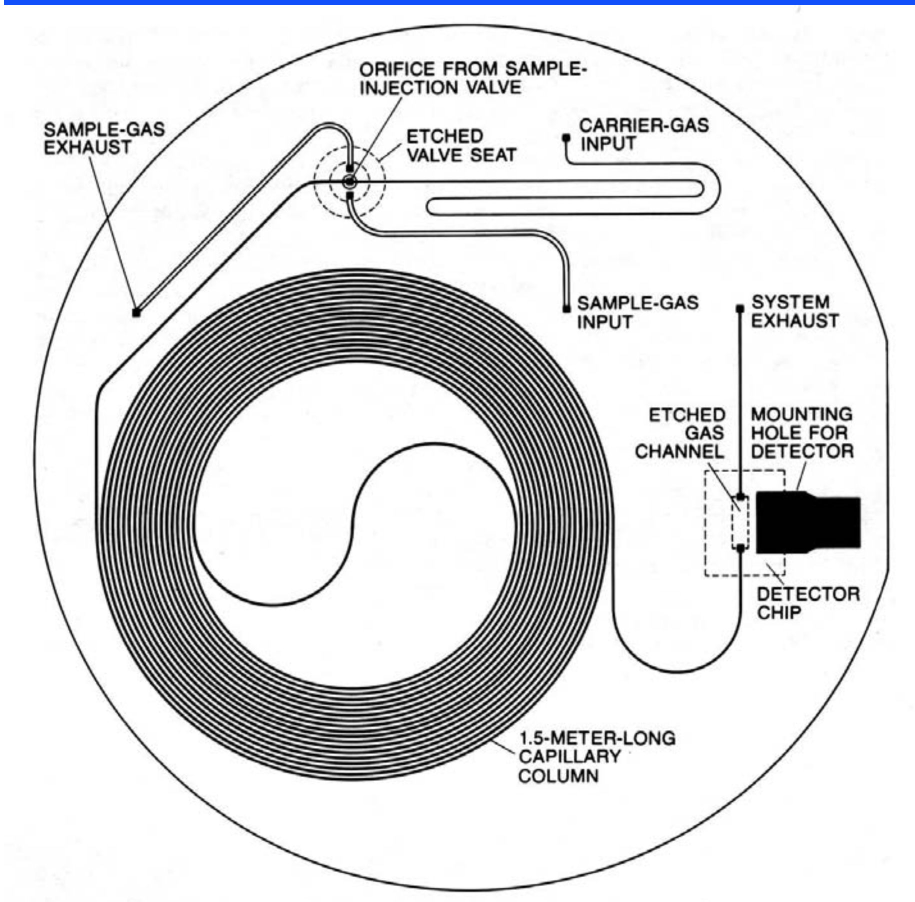
Reference: Barth, P. W., Beatty, C. C., Field, L. A, Baker, J. W., and Gordon, G. B., "A Robust, Normally-Closed Silicon Microvalve," Technical Digest, Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 248 - 250.

PACKAGING FOR FLUIDICS



Reference: Schomberg, W. K., Büstgens, B., Fahrenberg, J., and Maas, D., “Components for Microfluidic Handling Modules,” van den Berg, A., and Bergveld, P. [eds.], Proceedings of Micro Total Analysis Systems Conference (µTAS ’94), Twente, Netherlands, Nov. 21 - 22, 1994, pp. 255 - 258.

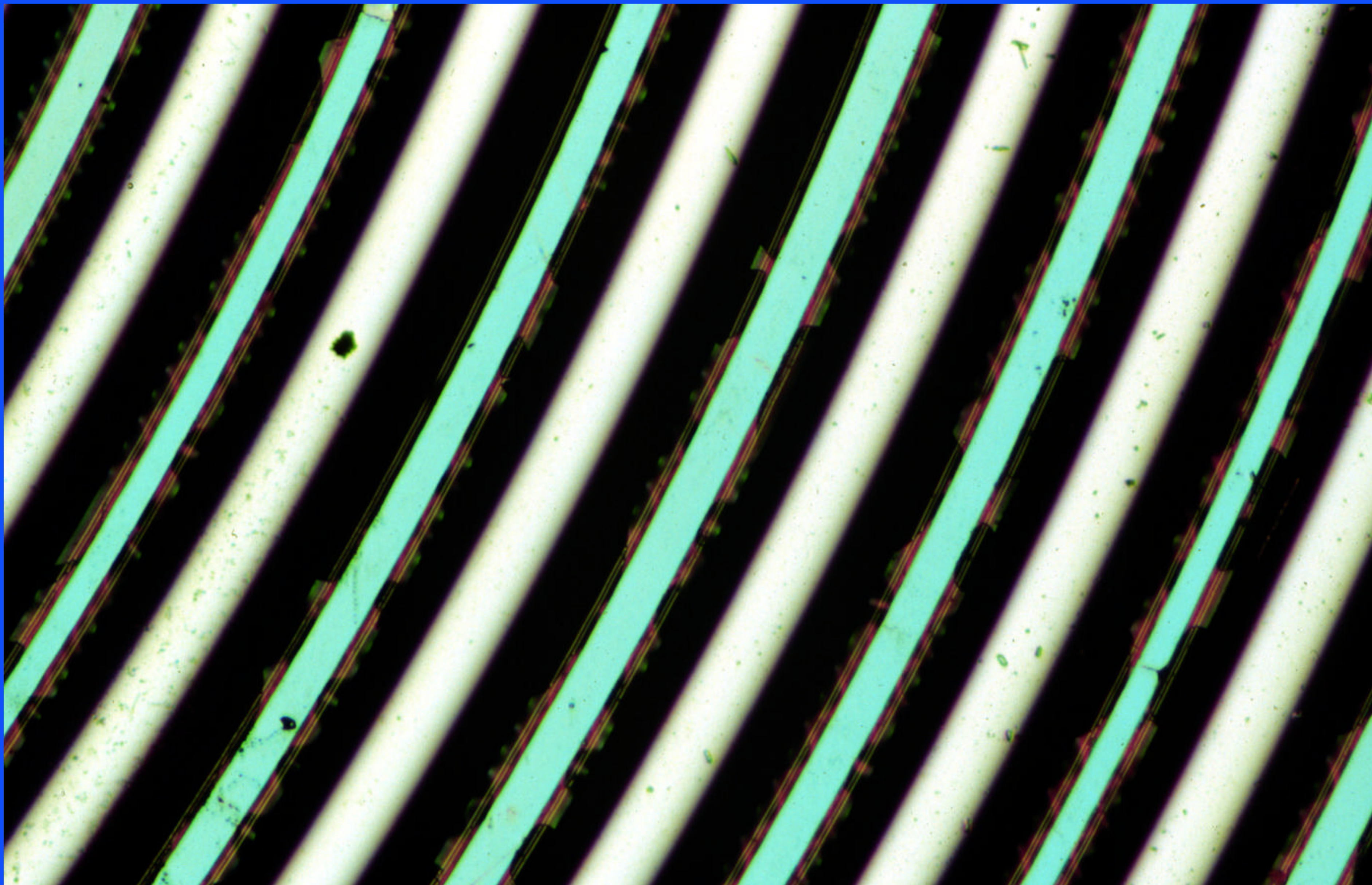
GAS CHROMATOGRAPHY SYSTEM

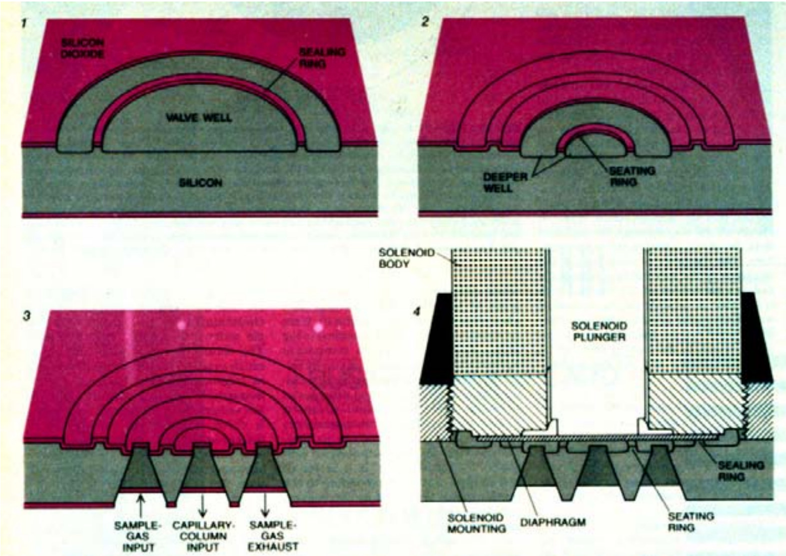


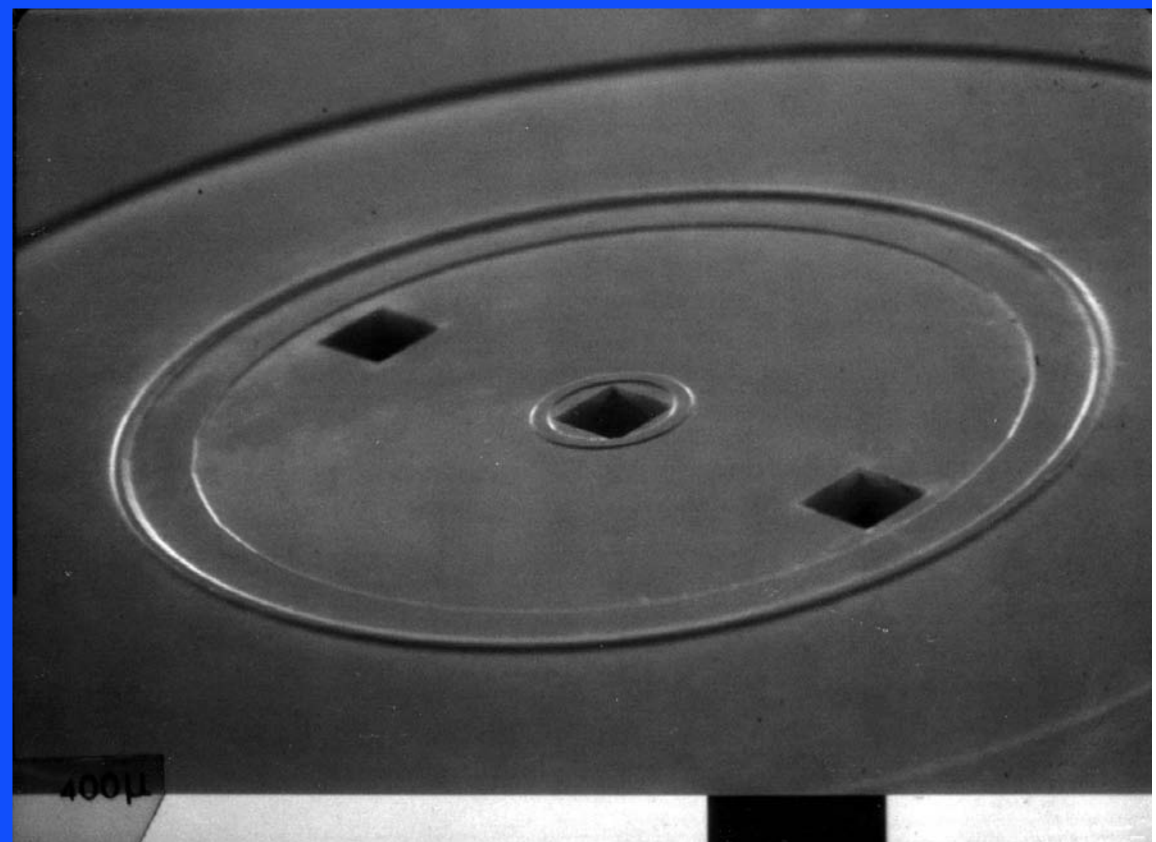
Source: Terry, S. C., Jerman, J. H., and Angell, J. B., "A Gas Chromatographic Air Analyzer Fabricated on a Silicon Wafer," IEEE Transactions on Electron Devices, vol. ED-26, no. 12, Dec. 1979, pp. 1880 - 1886.

Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.

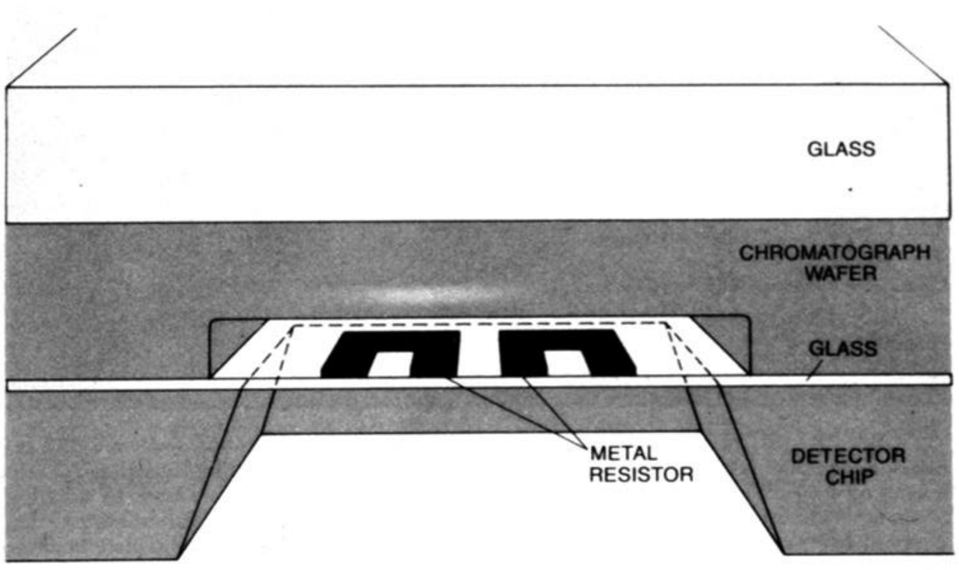
1.5 meter GC column on 2" wafer.

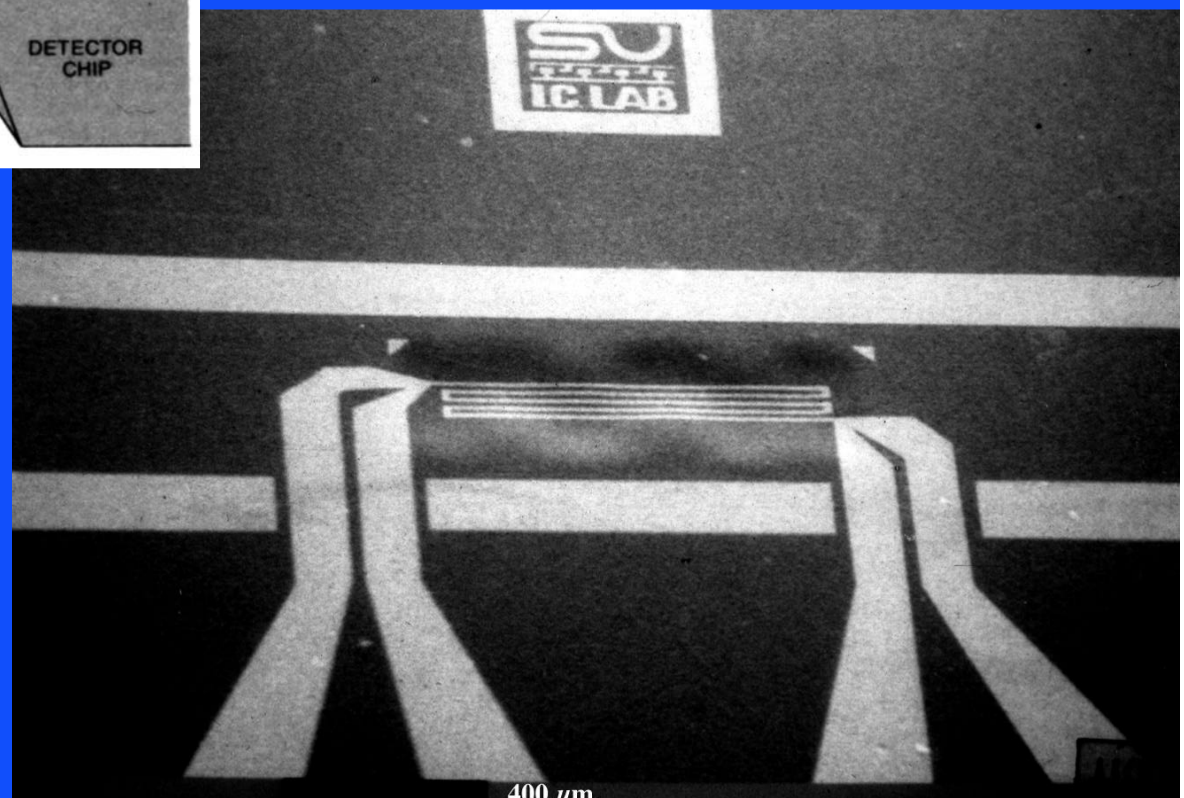




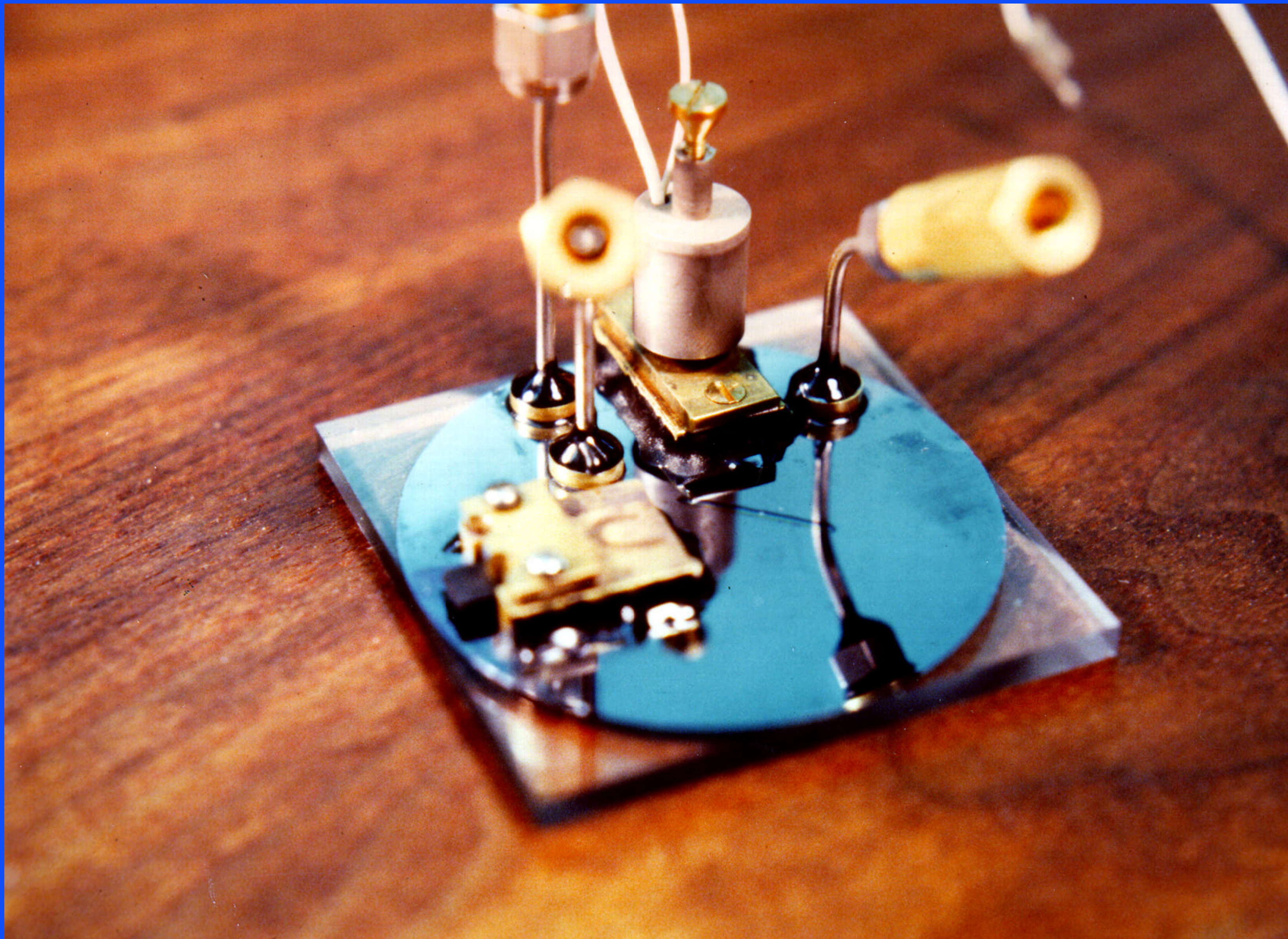


Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.

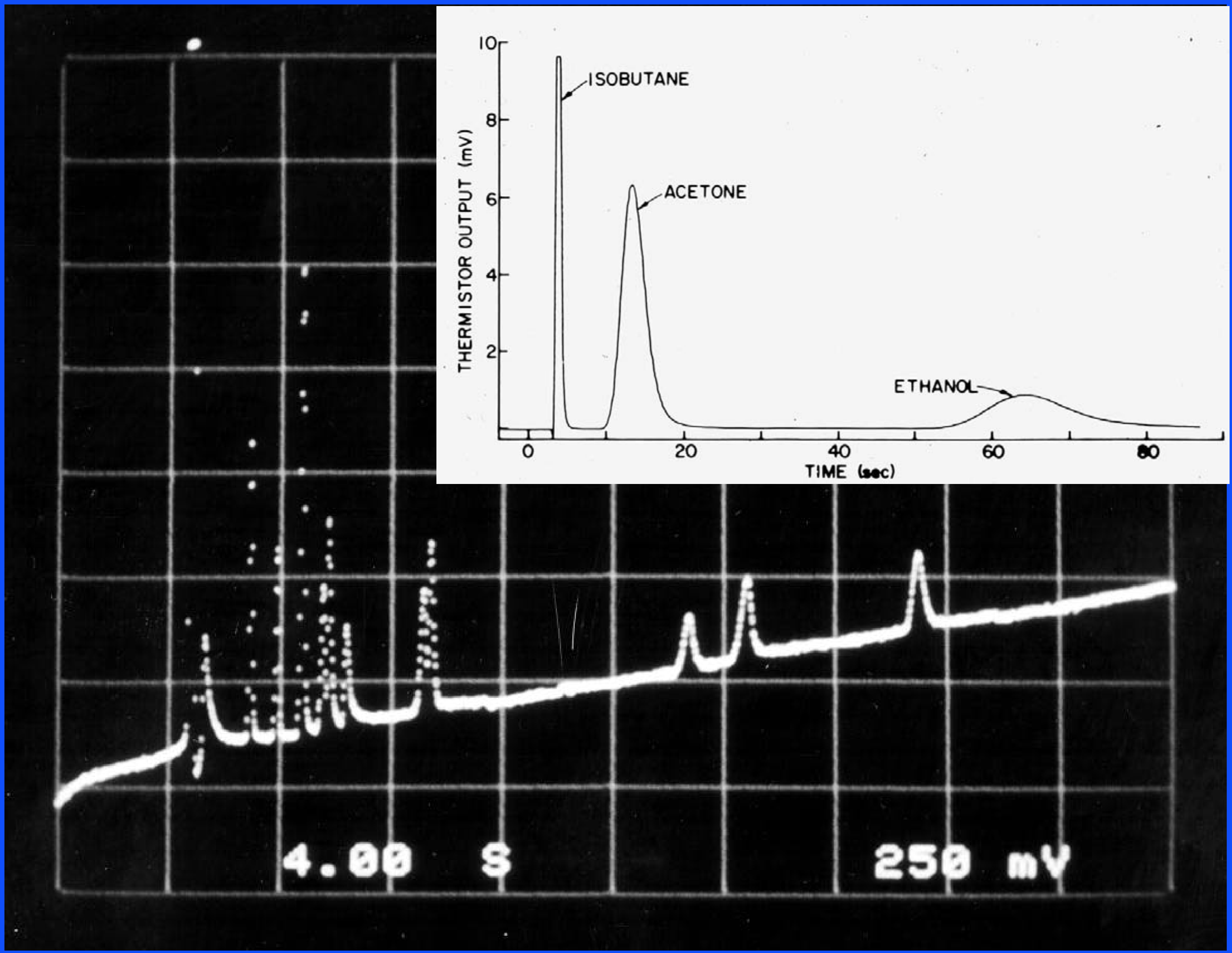




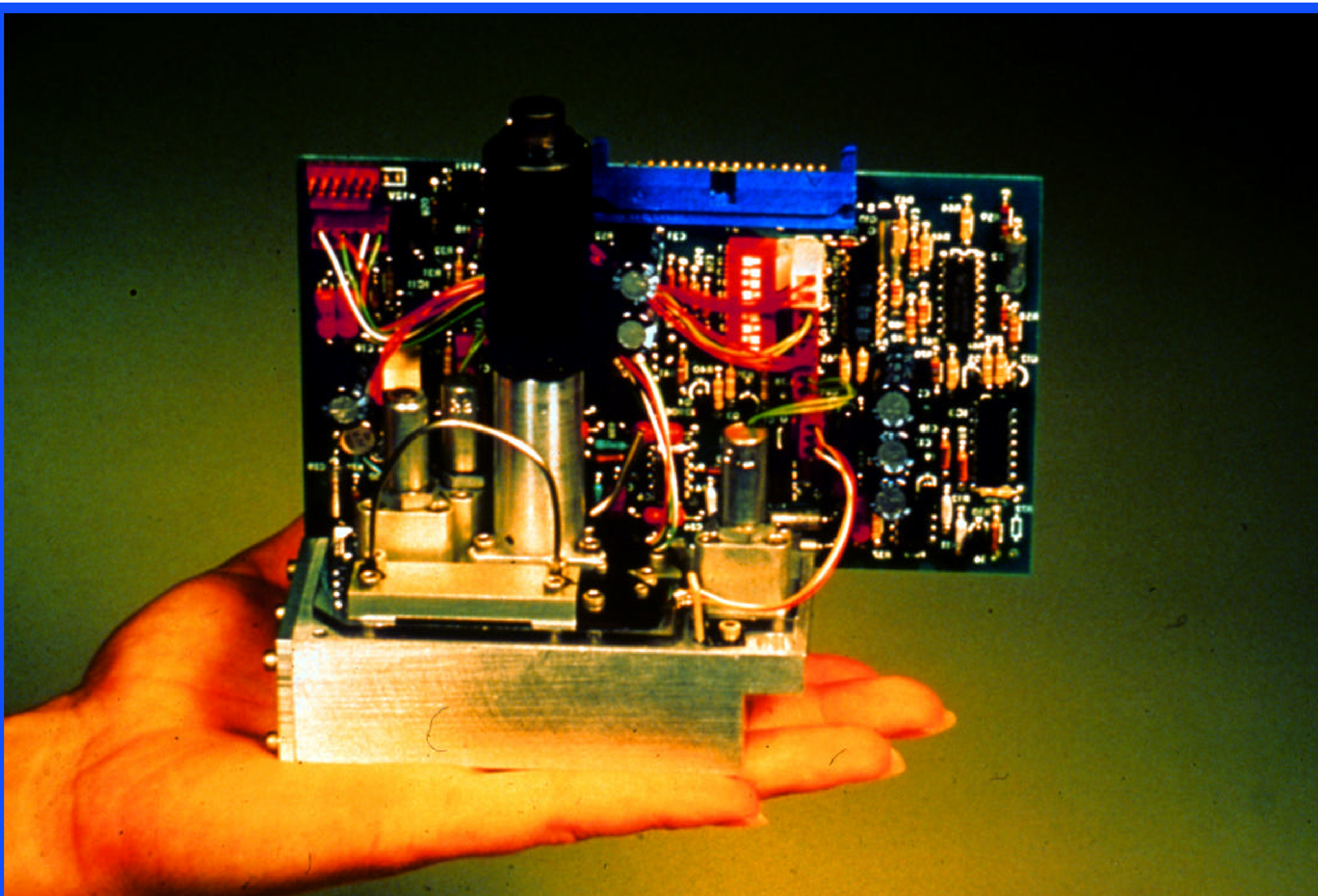
Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.



Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.



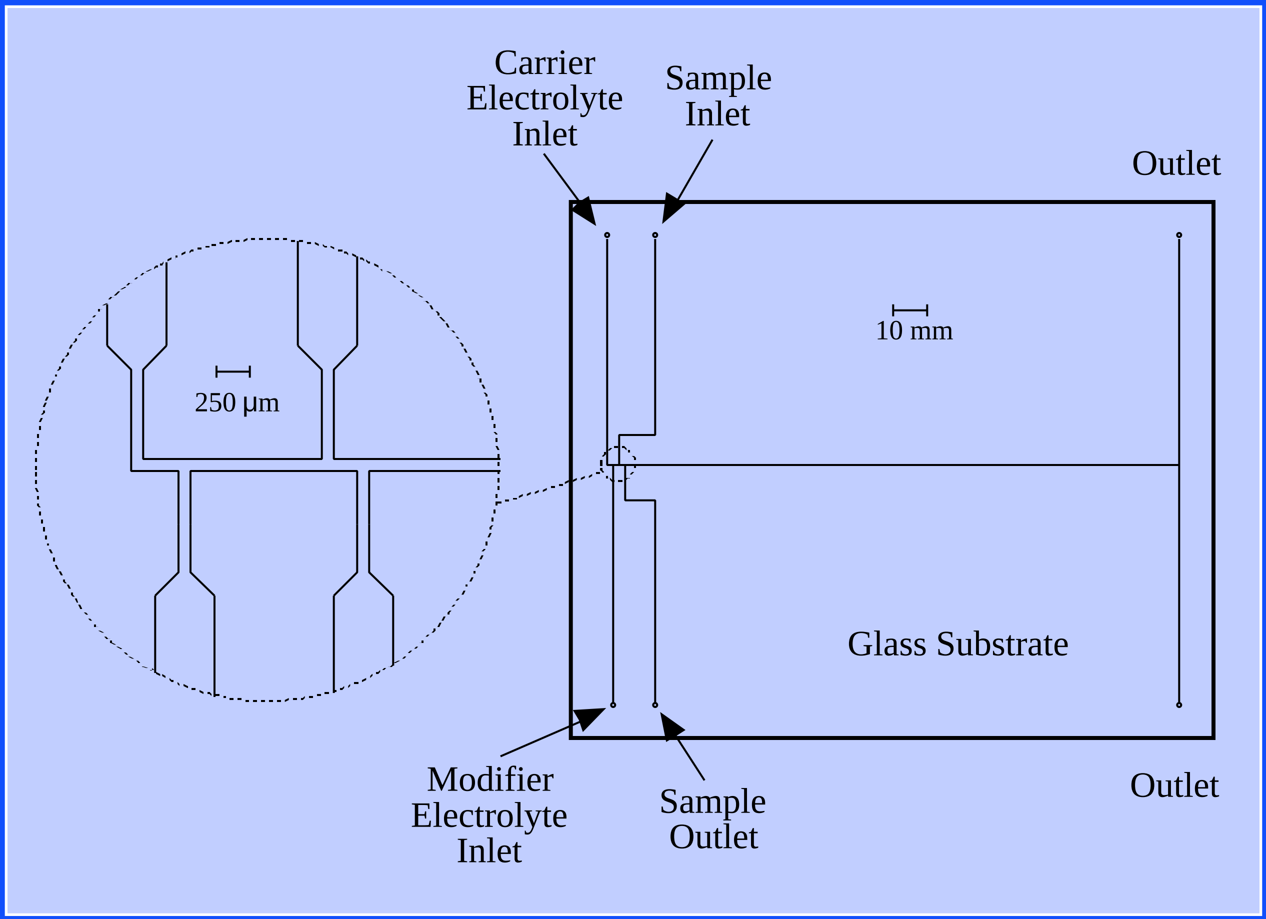
Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.



Courtesy Prof. K. Petersen, Stanford University.

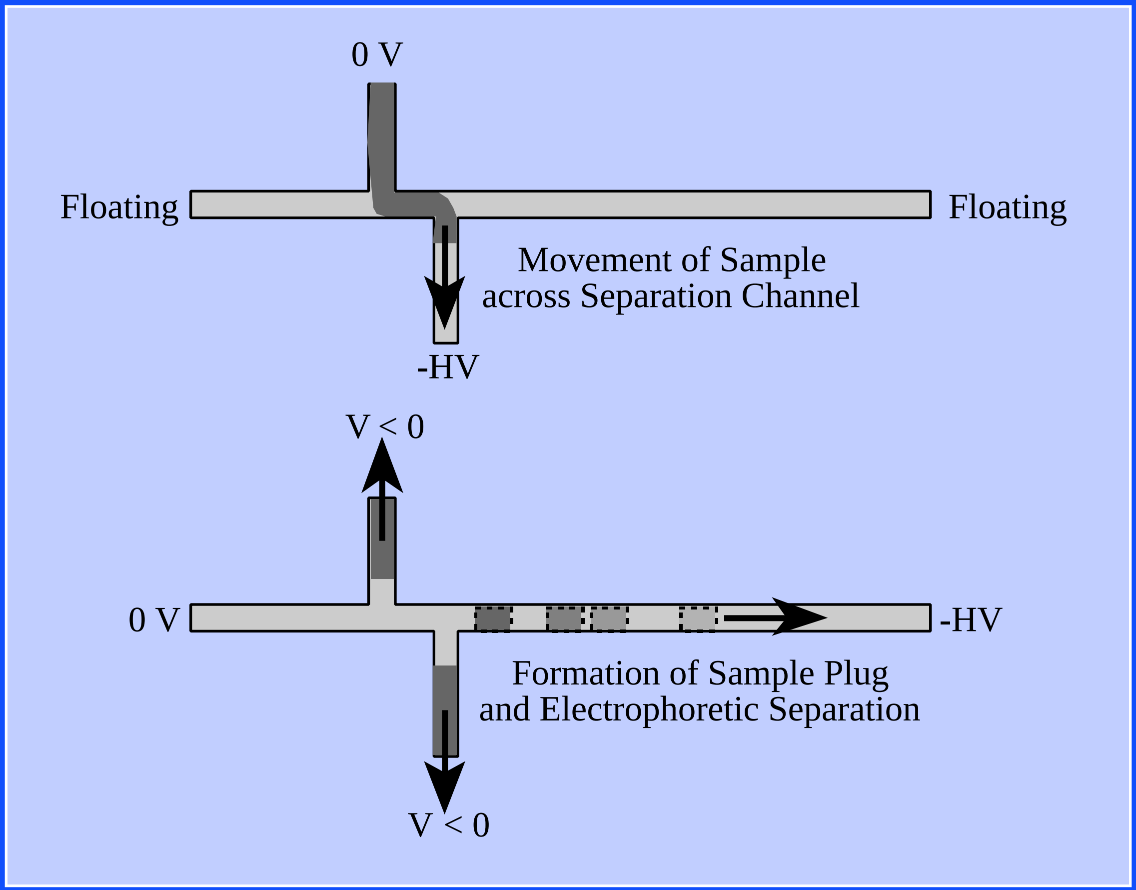
Courtesy Dr. S. Terry, EG&G IC Sensors, Inc.

ELECTROPHORESIS SYSTEMS



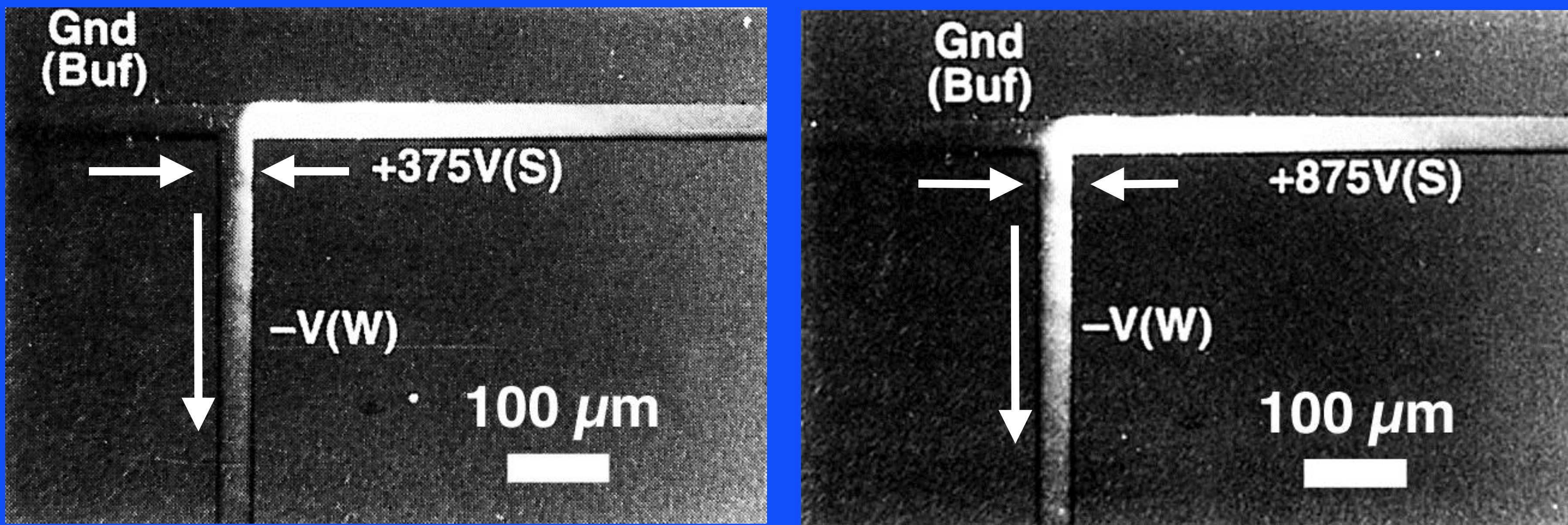
Reference: Manz, A., Verpoorte, E., Raymond, D. E., Effenhauser, C. S., Burggraf, N., and Widmer, H. M., "µ-TAS: Miniaturized Total Chemical Analysis Systems," in Proceedings of the Micro Total Analysis Systems Conference (µTAS '94), van den Berg, A., and Bergveld, P. [eds.], Twente, Netherlands, Nov. 21 - 22, 1994, Kluwer Academic Publishers, Dordrecht, Netherlands, 1995, pp. 181 - 190.

SAMPLE INJECTION



Reference: Harrison, D. J., Fan, Z., and Seiler, K., "Integrated Electrophoresis Systems for Biochemical Analyses," Proceedings of the 1994 Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 13 - 16, 1994, pp. 21 - 24.

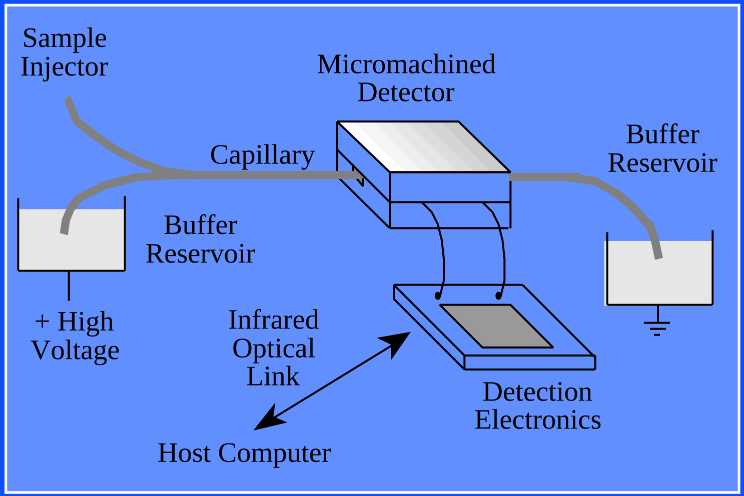
VOLTAGE CONTROLLED MIXING IN MICROMACHINED ELECTROPHORESIS SYSTEM

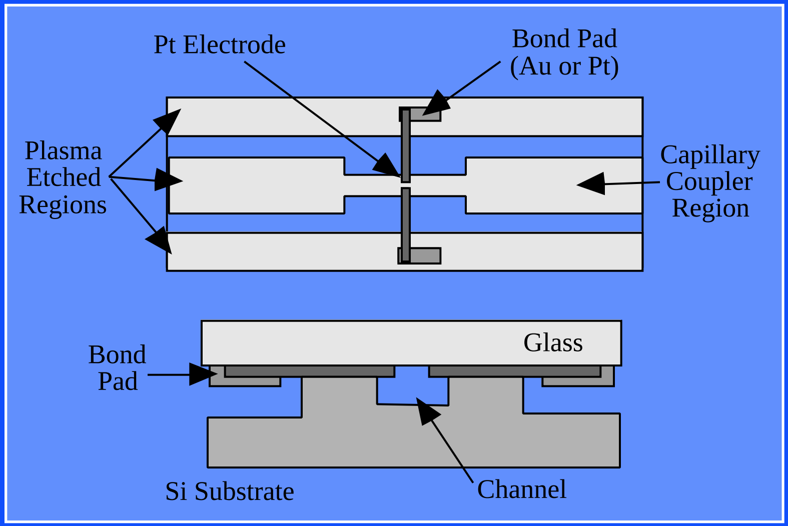


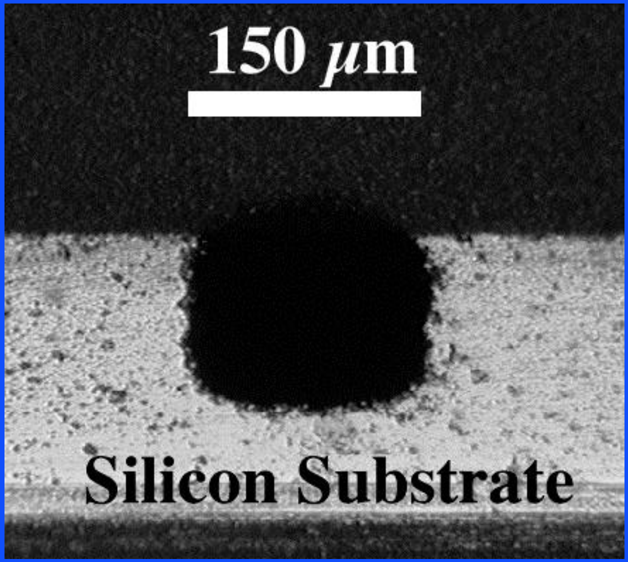
Variable proportions mixed under voltage control. (10 mM carbonate buffer, pH 9.1 [left] and 100 μM fluorescein [right])

Source: Harrison, D. J., Fluri, K., Fan, Z., and Seiler, K., "Integration of Analytical Systems Incorporating Chemical Reactions and Electrophoretic Separation," Micro Total Analysis Systems, Proceedings of μTAS '94 Workshop, Twente, Netherlands, Nov. 21 - 22, 1994 pp. 105 - 115.

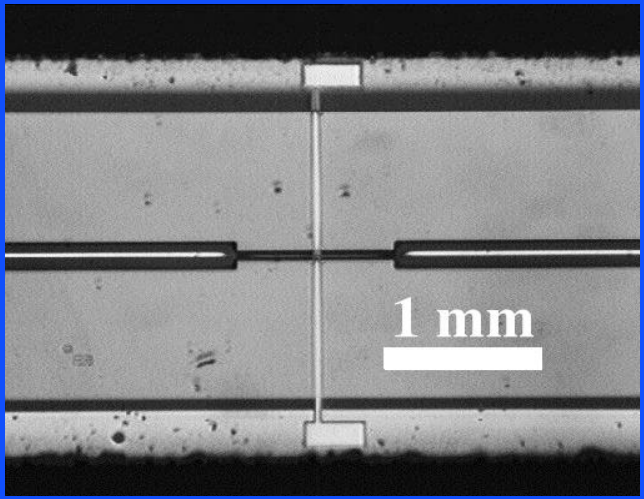
CONDUCTIVITY CELL FOR CAPILLARY ELECTROPHORESIS



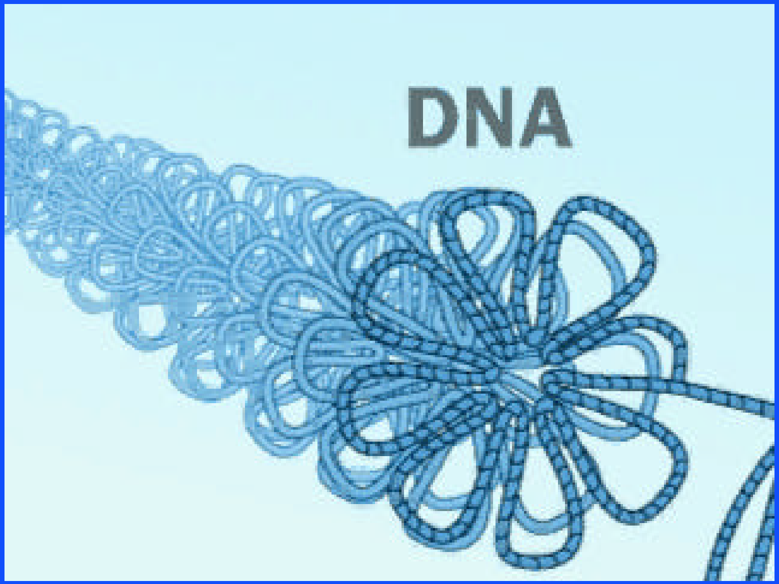


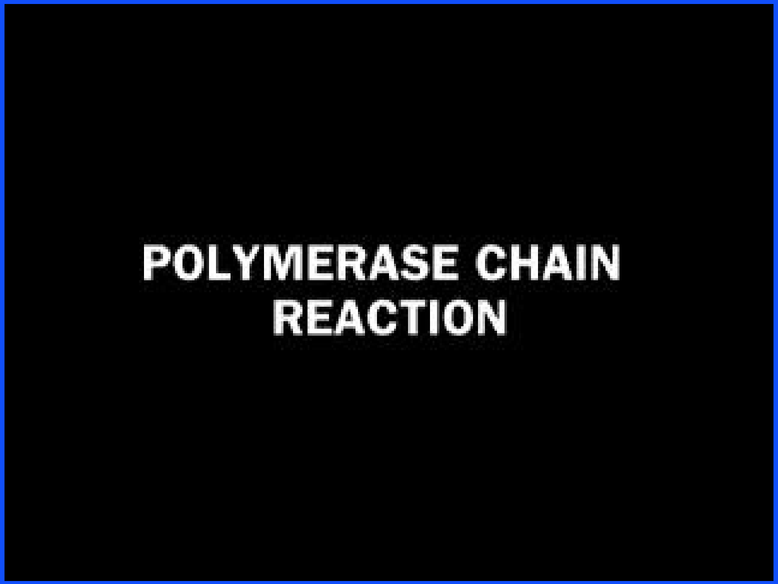


Reay, R. J., Dadoo, R., Storment, C. W., Zare, R. N., and Kovacs, G. T. A., "Microfabricated Electrochemical Detector for Capillary Electrophoresis," Proceedings of the Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 13 - 16, 1994, pp. 61 - 64.



POLYMERASE CHAIN REACTION SYSTEMS

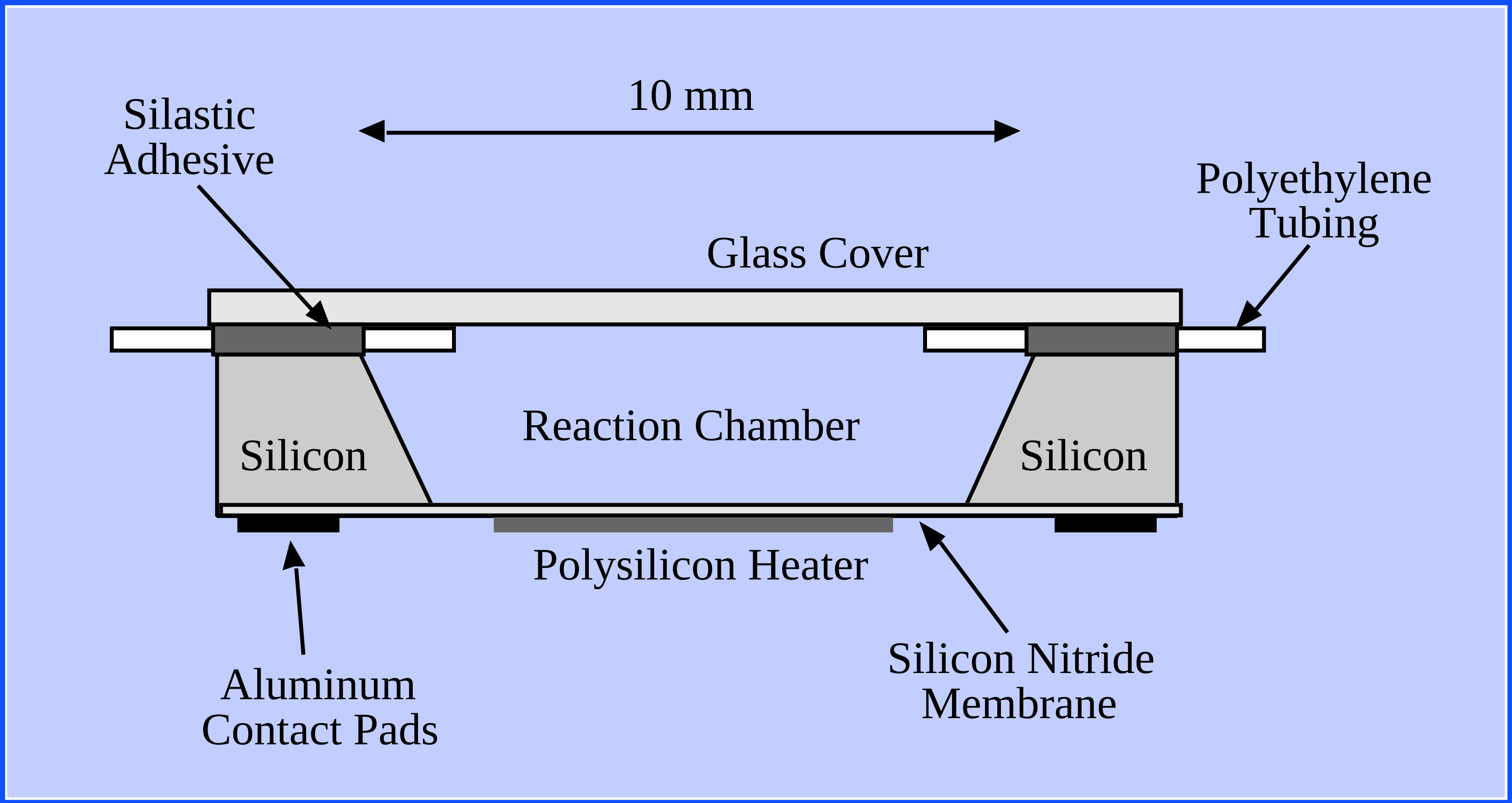




Courtesy Prof. H. C. Heller, Stanford University.

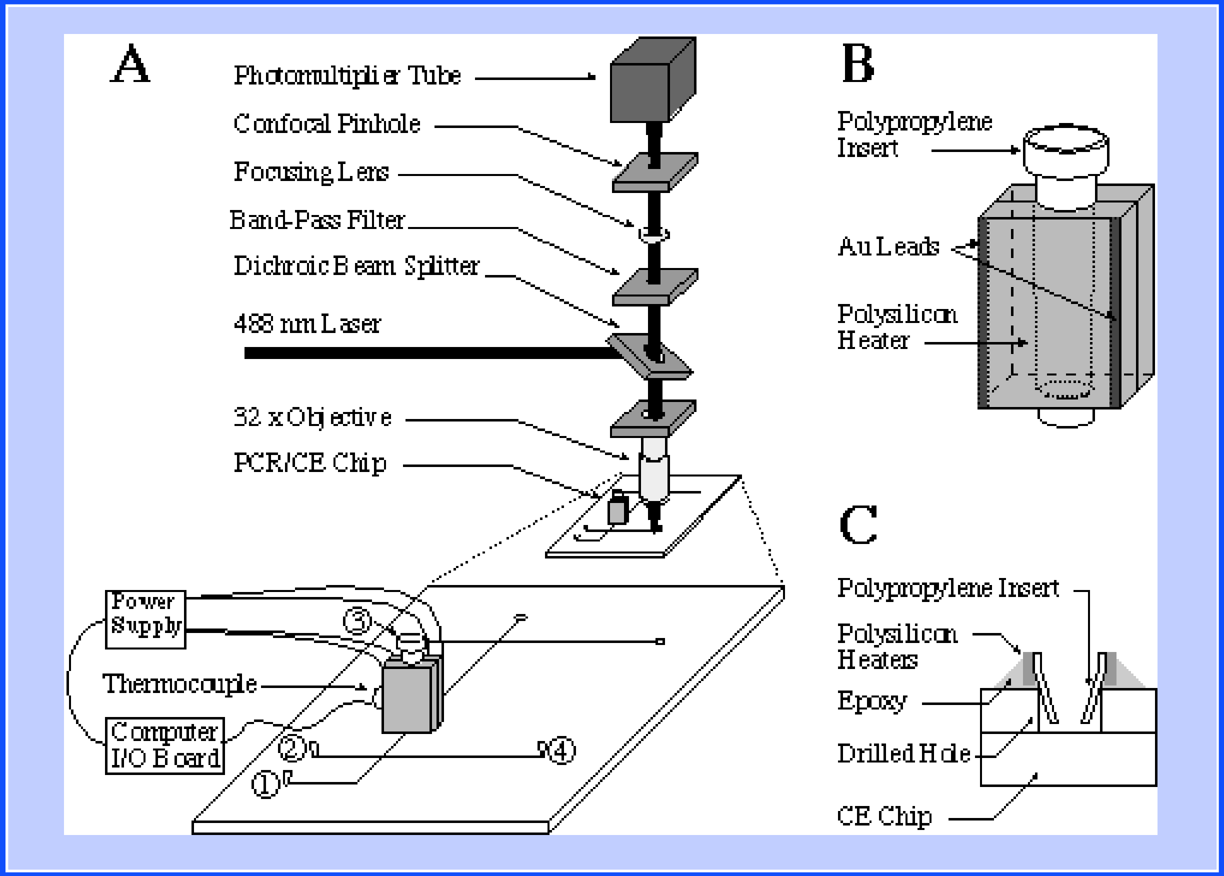
Source: Purves, Orians, Heller, and Sadava, "Life: The Science of Biology," Sinauer Associates/W.H. Freeman & Co., New York, 1999.

PCR REACTOR



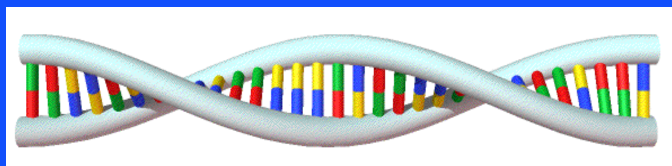
Reference: Northrup, M. A., Ching, M. T., White, R. M., and Watson, R. T., "DNA Amplification with a Microfabricated Reaction Chamber," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 924 - 926.

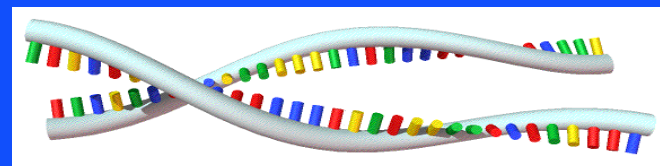
PCR COUPLED TO ELECTROPHORESIS



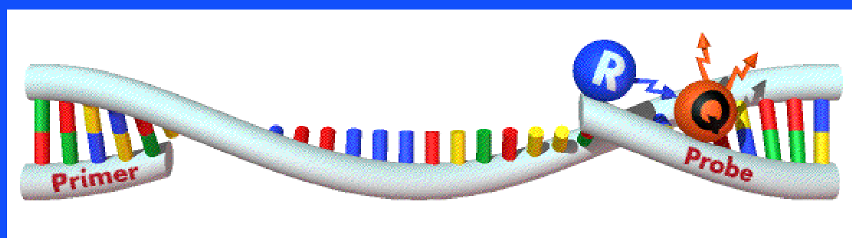
Reference: Woolley, A. T., Hadley, D., Landre, P., deMello, A. J., Mathies, R. A., and Northrup, M. A., "Functional Integration of PCR Amplification and Capillary Electrophoresis in a Microfabricated DNA Analysis Device," Analytical Chemistry, vol. 68, no. 23, Dec. 1996, pp. 4081 - 4086.

PCR TAQMAN™ DNA AMPLIFICATION

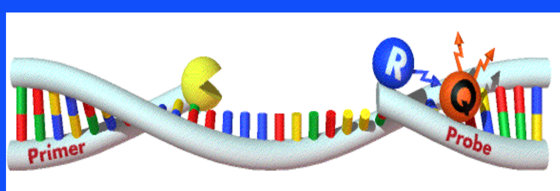


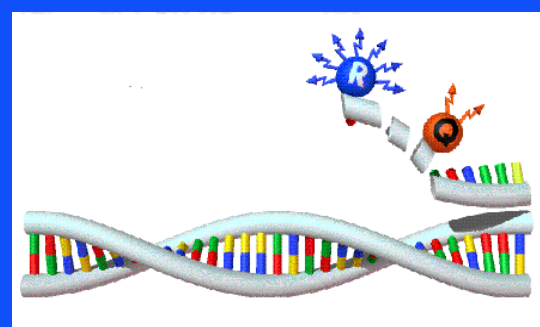


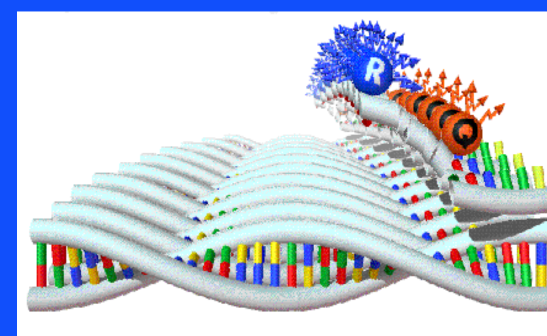
Denature DNA



Anneal Primer & Probe







Polymerize

Increase Fluorescence

Repeat N-times

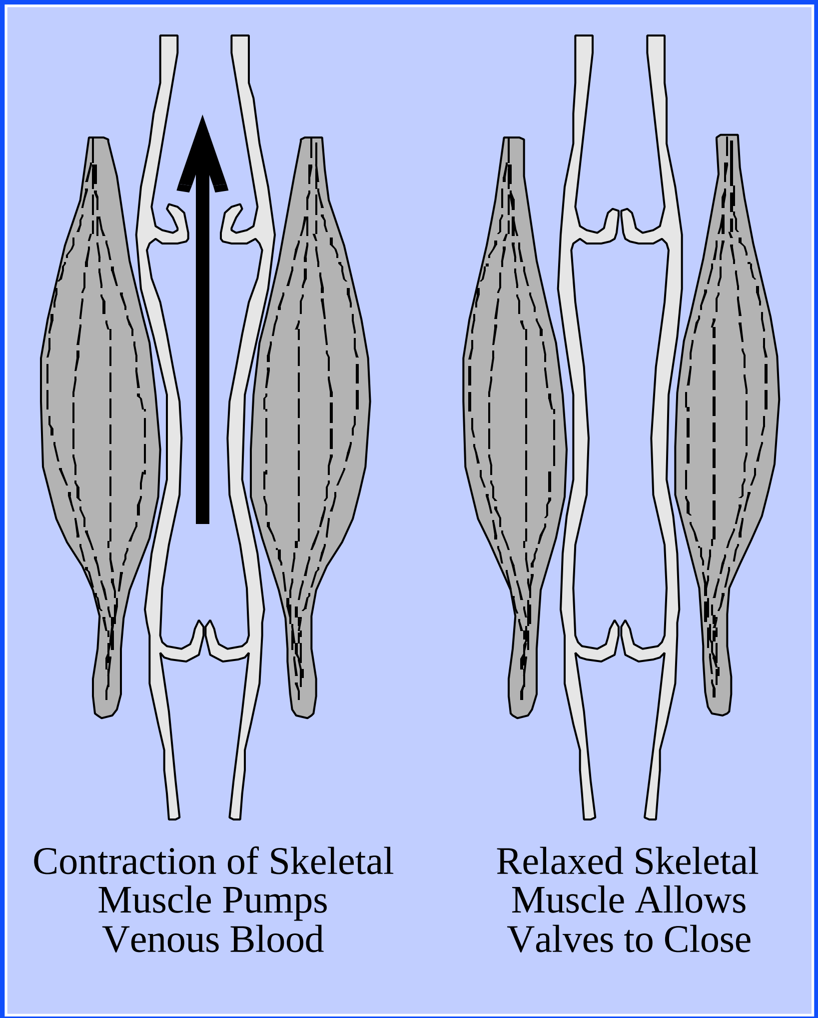
Courtesy Perkin-Elmer, Applied Biosystems Division. TAQMAN is ™ of Roche, Inc.

BIOLOGICAL FLUIDIC SYSTEMS

Vessel	Diameter (cm)	Total Area (cm^2)	Length (cm)	Wall Thickness (cm)	Average Pressure (mm Hg)	Average Velocity (cm/s)
Aorta	2.5	5	50	0.2	100 ± 20	48
Arteries	0.4	24	50	0.1	90 ± 20	45
Arterioles	0.005	40	1	0.02	60 ± 5	5
Capillaries	0.0008	2,500	0.1	0.0001	20	0.1
Venules	0.002	250	0.2	0.0002	10	0.2
Veins	0.5	100	2.5	0.05	5	1.0
Vena Cava	3.0	7	50	0.15	1	38

References: Mazumdar, J. N., "Biofluid Mechanics," World Scientific Press, River Edge, NJ, 1992, and Fay, J. A., "Introduction to Fluid Mechanics," MIT Press, Cambridge, MA, 1994.

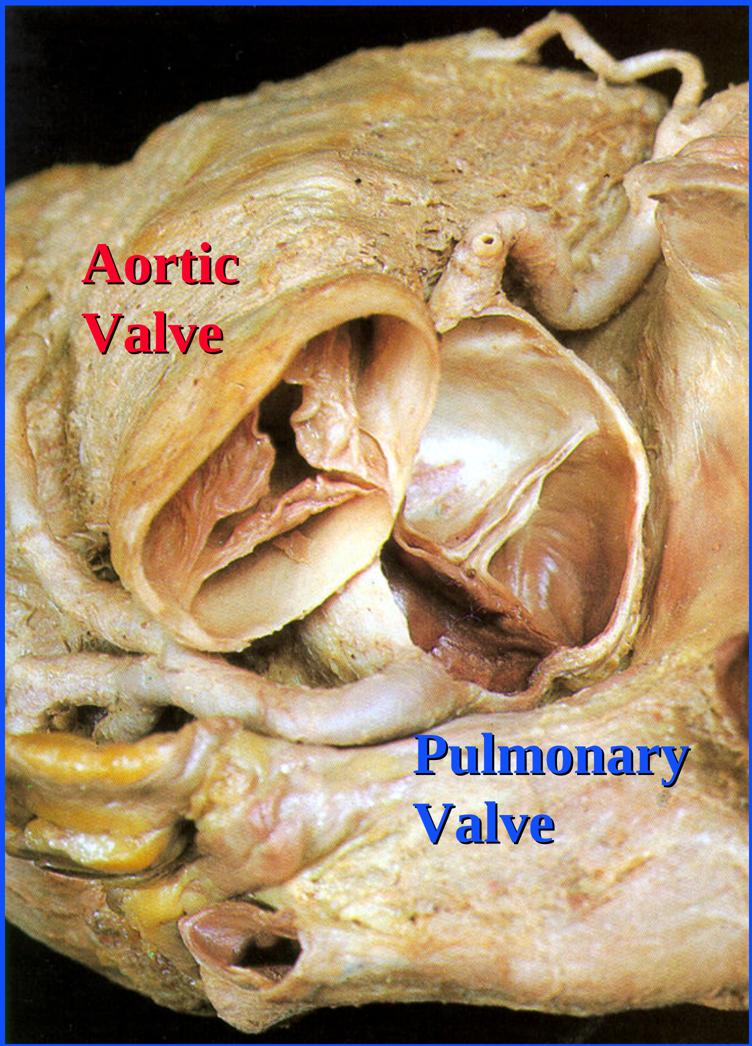
VENOUS VALVES



Reference: Tortora, G. J., and Anagnostakos, N. P., "Principles of Anatomy and Physiology," Harper and Row Publishers, New York, NY, 1987.

Source: Gosling, J. A., Harris, P. F., Humpherson, J. R., Whitmore, I., and Willan, P. L. T., "Atlas of Human Anatomy," J. B. Lippincott Co., Philadelphia, PA, 1985.

HEART VALVES



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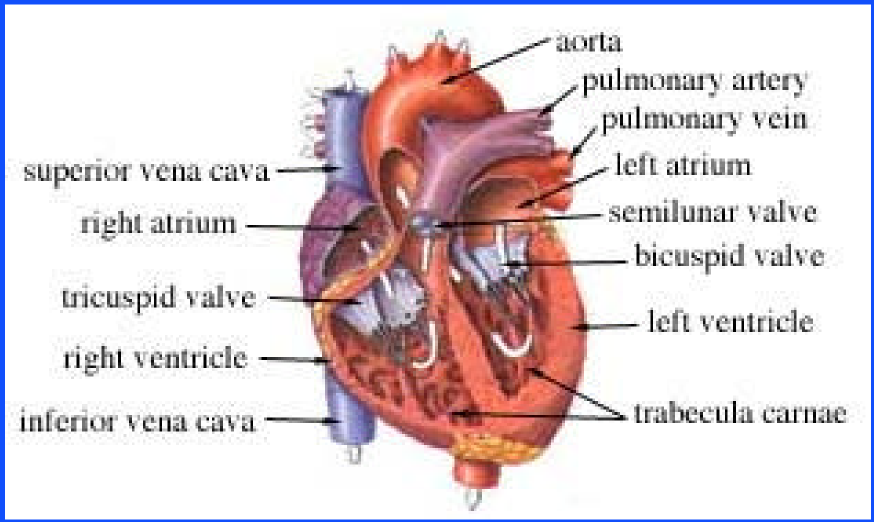
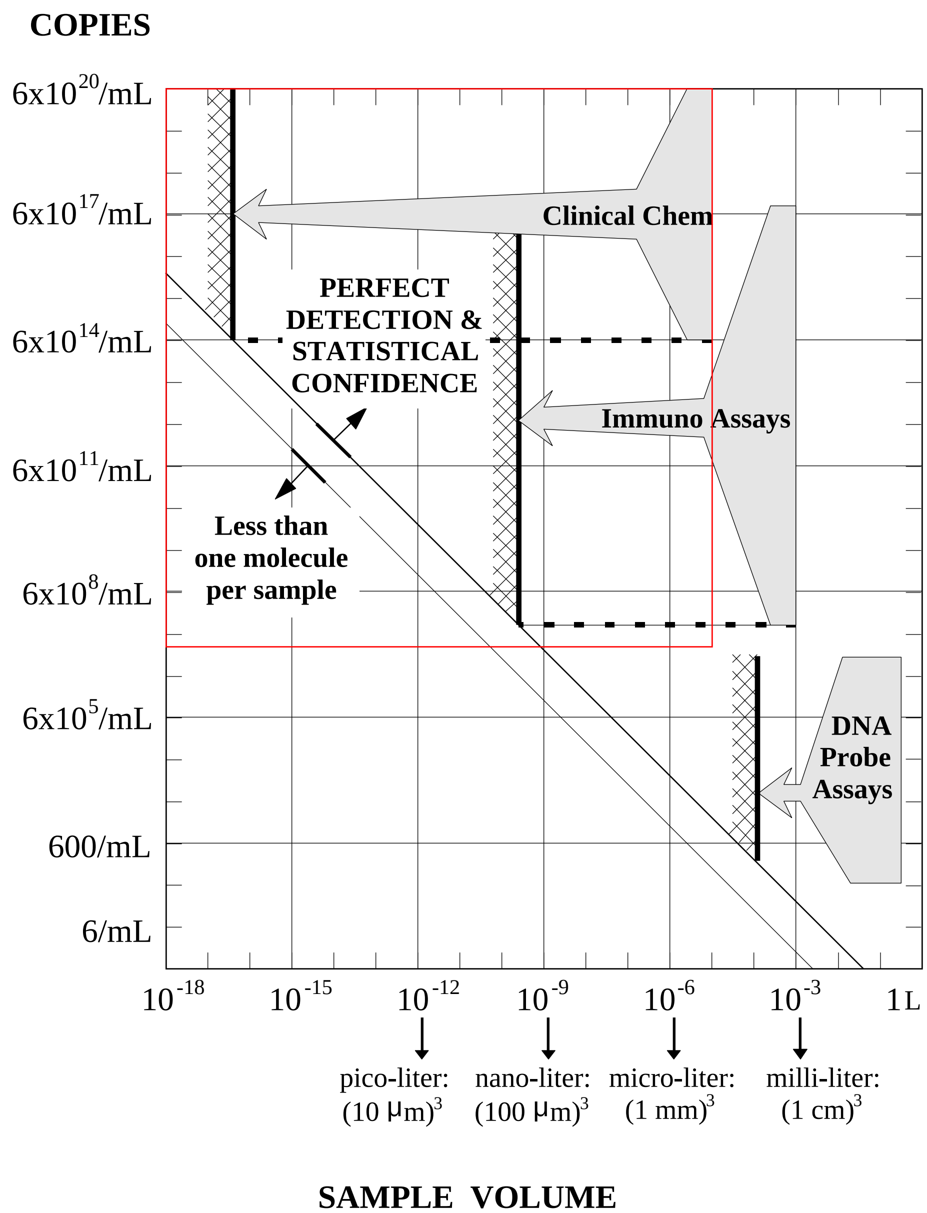
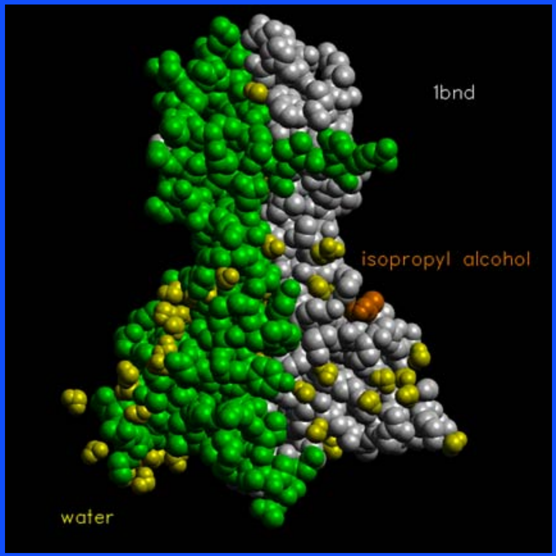


Source: http://www.bhs.berkeley.k12.ca.us/departments/science/anatomy/anatomy97/heart/scans/flow2.jpg

DETECTION LIMITS OF MICROFLUIDIC ASSAYS





Courtesy Dr. Kurt Petersen, Cepheid, Inc.

ISSUES FOR MICROFLUIDIC SYSTEMS

- Interconnect
- Fouling
- Purging
- Carryover
- Disposable or reusable?