Microelectromechanical Systems (MEMs) Applications – Valves and Pumps

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REVIEW

Valves and Pumps

- Valves
  - Flap
  - Diaphragm
- Pumps
  - Rotary
  - Diaphragm Pump
  - Peristaltic

- Actuation
  - Heat
  - Piezoelectric
  - Electrostatic
  - Magnetic

OUTLINE

Introduction

Basic Flapper and Diaphragm Valve

Micromachined Silicon Microvalve, T. Ohnstein, et.el., Sensor and System Development Center, Honeywell, Inc., Bloomington, Minnesota, Proceedings of the IEEE Micro Electro Mechanical Systems Conference, February 1990.

A Pressure-Balanced Electrostatically Actuated Microvalve, M. A. Huff, et.el., MIT, Cambridge, MA, Technical Digest of the IEEE Solid-State Sensor and Actuator Workshop, June 1990.

OUTLINE

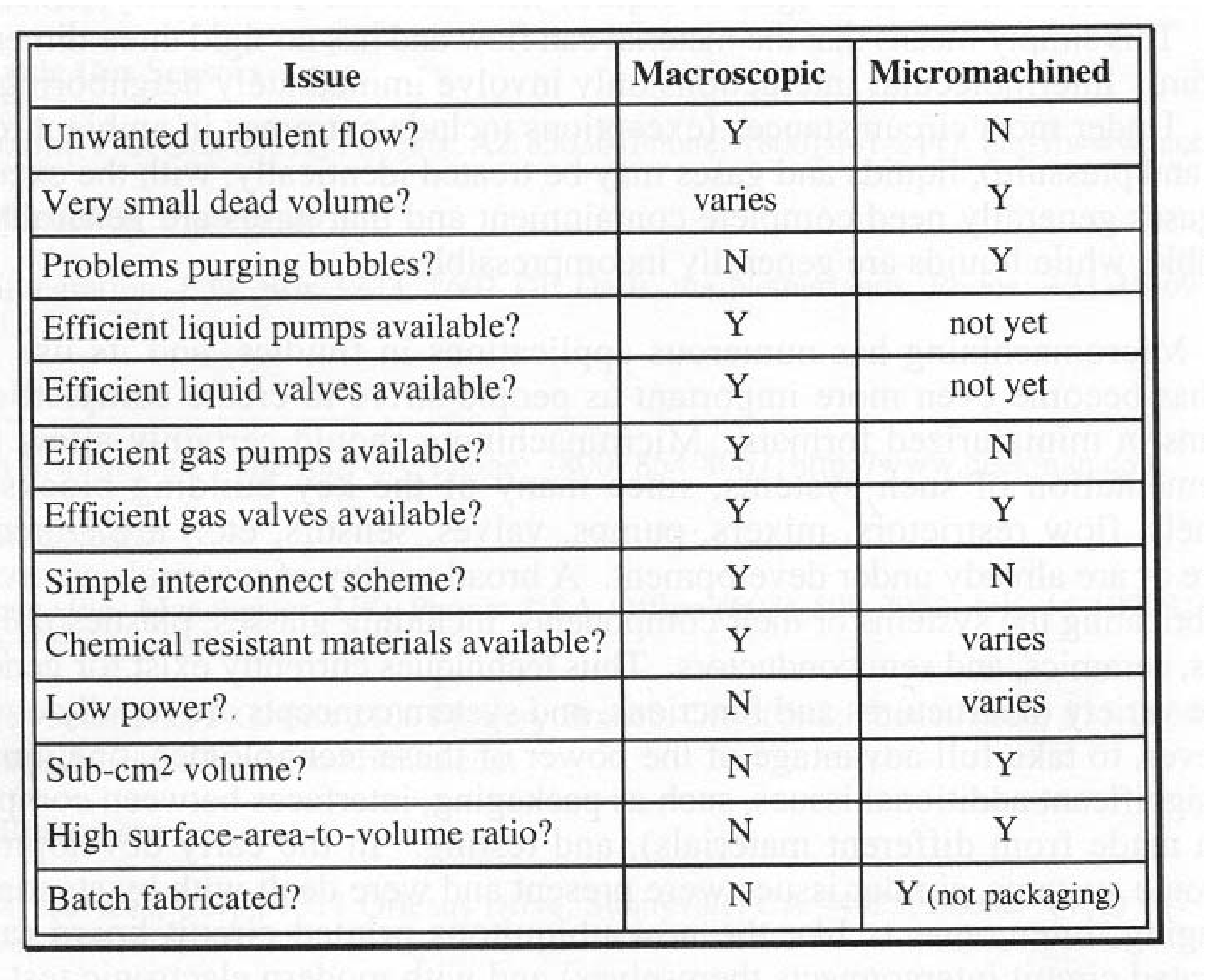
Basic Diaphragm and Peristaltic Pumps

A Thermopneumatic Micropump Based on Micro-engineering Techniques, F.C. M. Van De Pol, et. el., University of Twente, Department of Electrical Engineering, Enschede, The Netherlands, Proceedings of 5th International Conference on Solid-State Sensors and Actuators, June 1990

Piezoelectrically Actuated Miniature Peristaltic Pump, Y. Bar-Cohen, JPL/Caltech, Pasadena, CA, SPIE's 7th Annual International Symposium on Smart Structures and Materials, March 1-5, 2000, Newport CA.

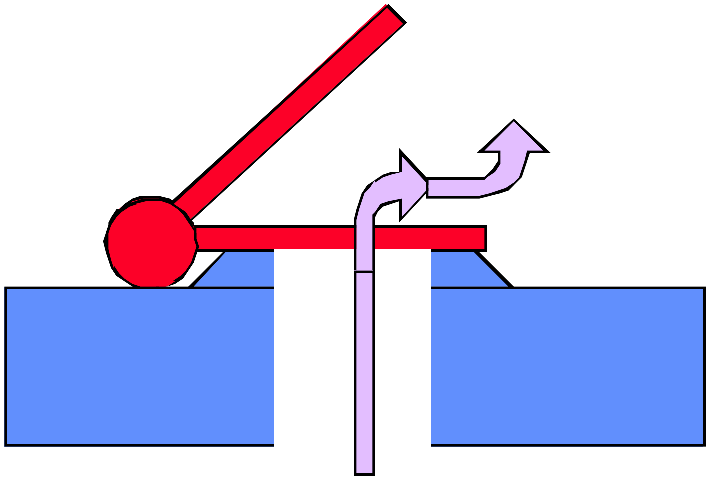
Thermally Actuated Peristaltic Pump Design, Vinay V. Abhyankar, Lynn F. Fuller, RIT, January 22, 2002

INTRODUCTION

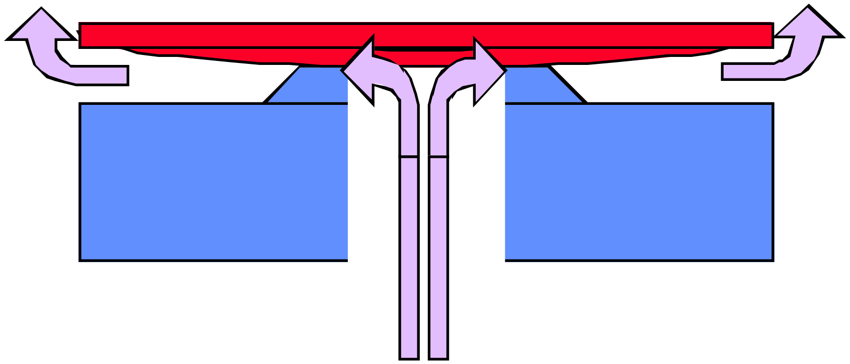


Issue	Macroscopic	Micromachined
Unwanted turbulent flow?	Y	N
Very small dead volume?	varies	Y
Problems purging bubbles?	N	Y
Efficient liquid pumps available?	Y	not yet
Efficient liquid valves available?	Y	not yet
Efficient gas pumps available?	Y	N
Efficient gas valves available?	Y	Y
Simple interconnect 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)

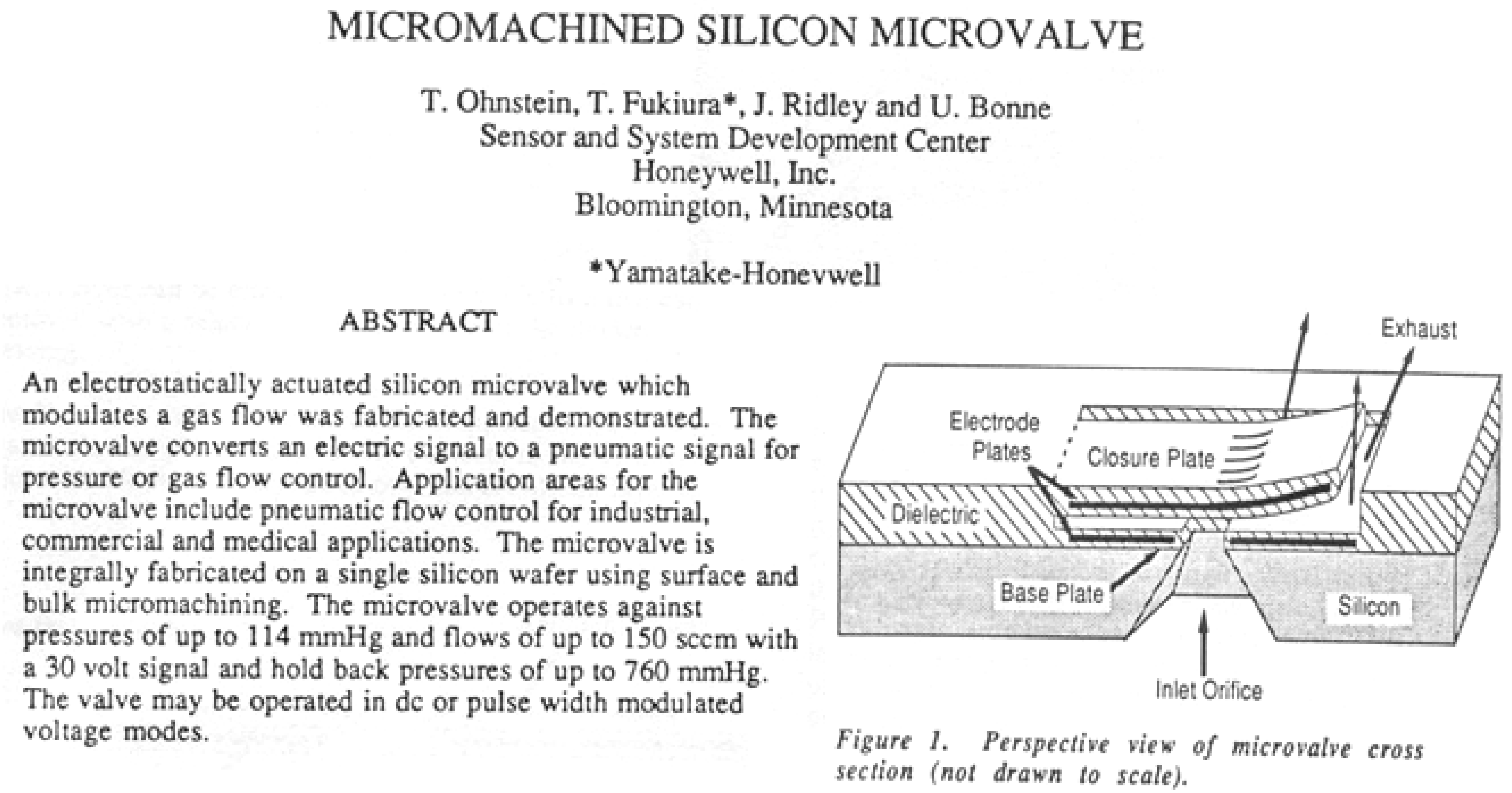
FLAPPER VALVES



DIAPHRAGM VALVE



AN ELECTROSTATIC FLAPPER VALAVE



MICROMACHINED SILICON MICROVALVE

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Sensor and System Development Center
Honeywell, Inc.
Bloomington, Minnesota

*Yamatake-Honevwell

ABSTRACT

An electrostatically actuated silicon microvalve which modulates a gas flow was fabricated and demonstrated. The microvalve converts an electric signal to a pneumatic signal for pressure or gas flow control. Application areas for the microvalve include pneumatic flow control for industrial, commercial and medical applications. The microvalve is integrally fabricated on a single silicon wafer using surface and bulk micromachining. The microvalve operates against pressures of up to 114 mmHg and flows of up to 150 sccm with a 30 volt signal and hold back pressures of up to 760 mmHg. The valve may be operated in dc or pulse width modulated voltage modes.

Figure 1. Perspective view of microvalve cross section (not drawn to scale).

AN ELECTROSTATIC FLAPPER VALAVE

Normally-open Valve
Closure Plate
350 µm x 390 µm
Inlet Orifice
24 µm x 60 µm

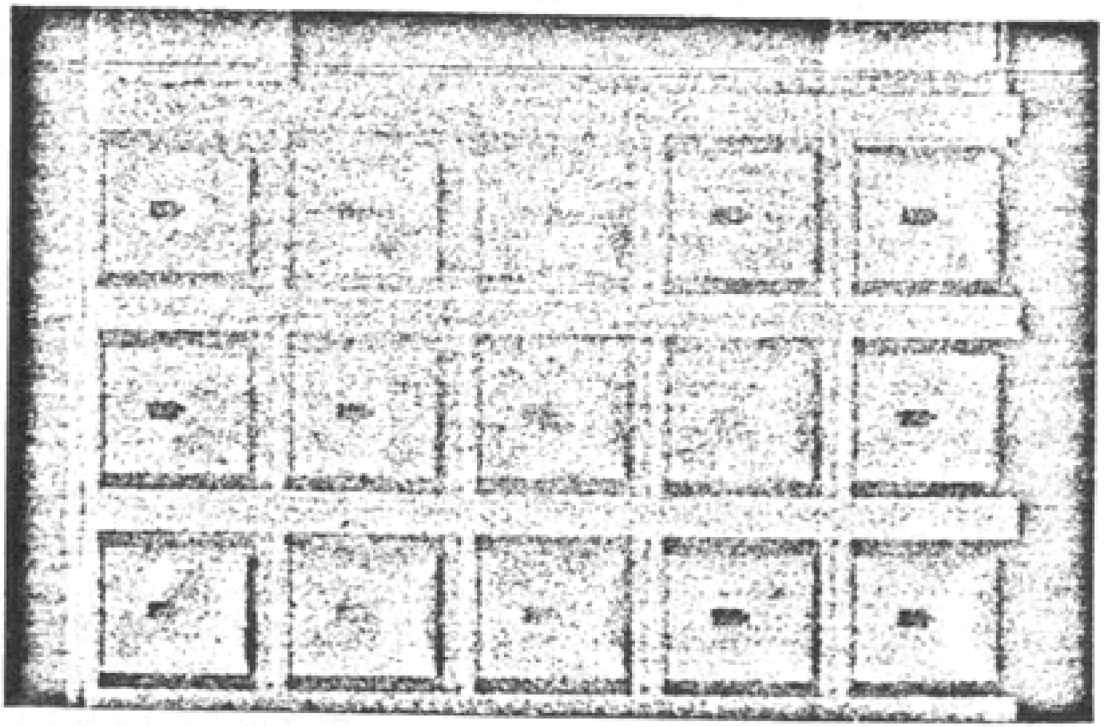


Figure 2. Photomicrograph of the top view of a microvalve. The device consists of a 5 x 5 array of cantilever closure plate/orifice valves connected in parallel. The array is truncated in the photograph.

AN ELECTROSTATIC FLAPPER VALAVE

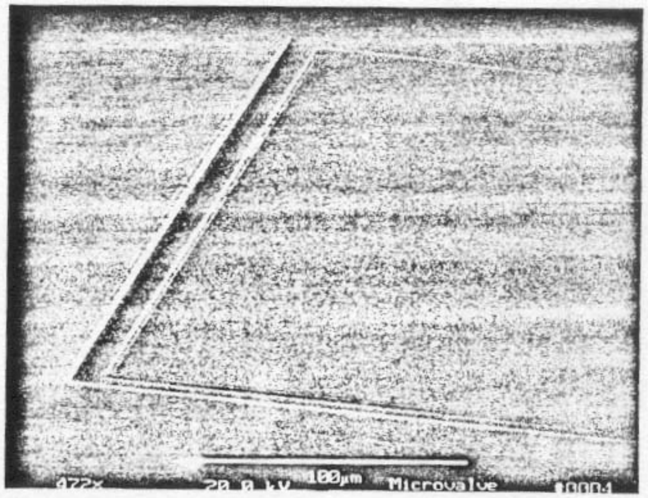


Figure 4. SEM photograph of one cantilever closure plate. The cantilever is attached at the right side, out of the photograph view, and extends to the left in the photograph.

Metal electrodes (did not say, guess W)
4 Nitride Layers
Oxide or Aluminum Sacrificial Layer

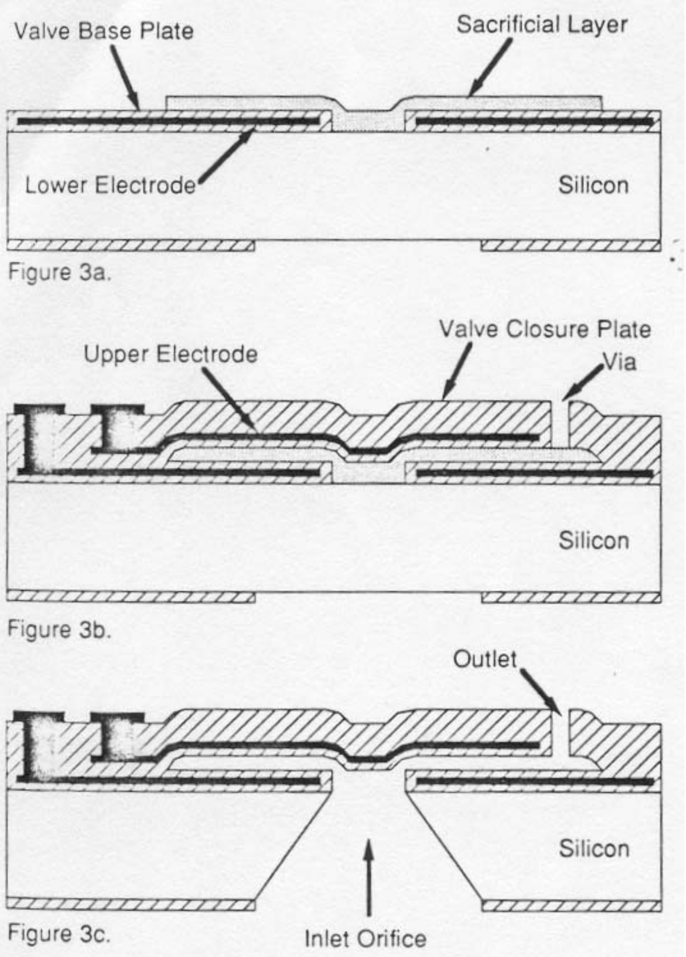


Figure 3a.

Figure 3b.

Figure 3c.

Figure 3. Cross Section views of the microvalve showing the major fabrication steps (not drawn to scale).

AN ELECTROSTATIC FLAPPER VALAVE

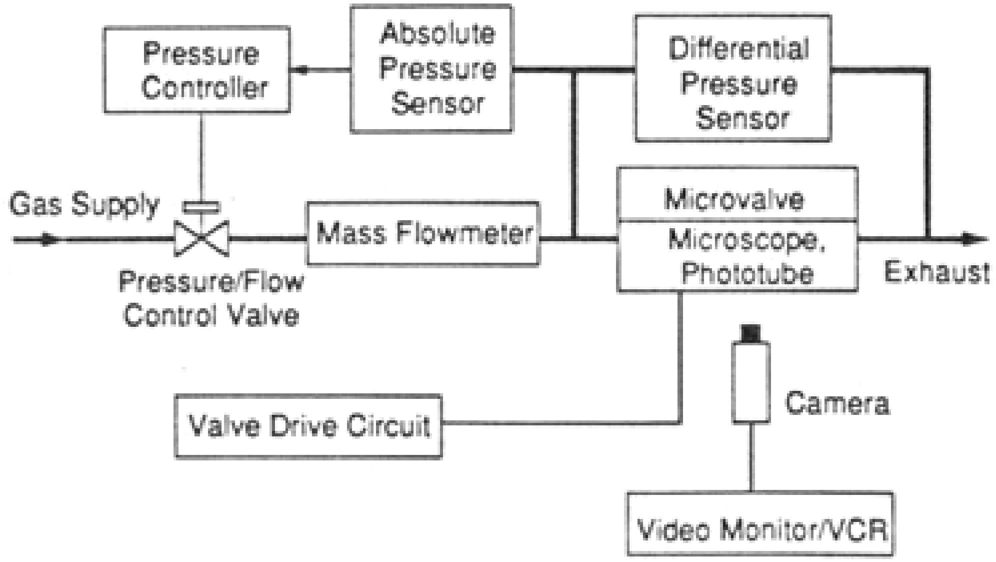


Figure 6. Diagram of the microvalve test station.

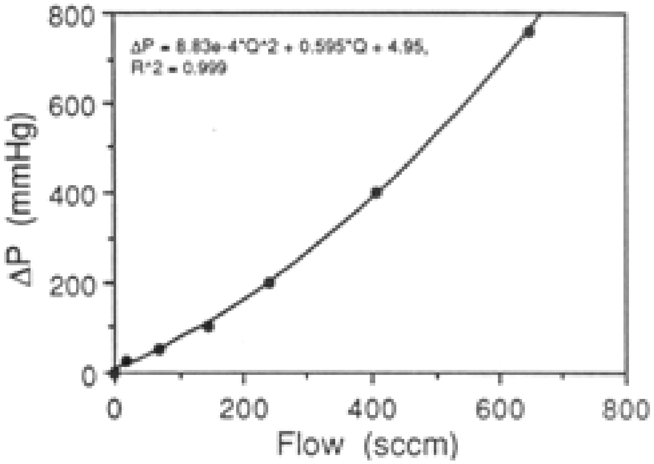


Figure 7. The microvalve orifice flow characteristic measured with the microvalve in the unenergized, "open" position.

AN ELECTROSTATIC FLAPPER VALAVE

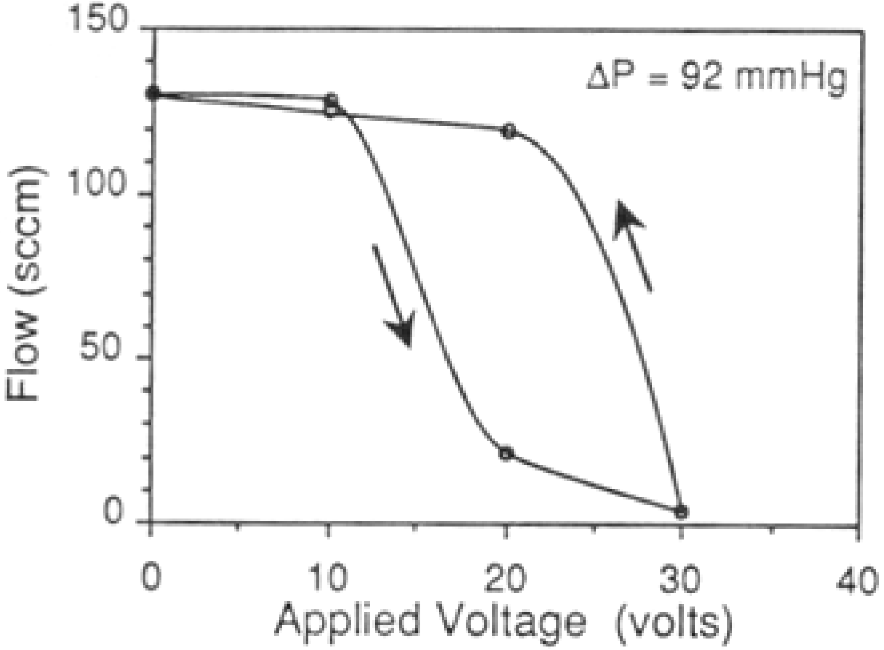
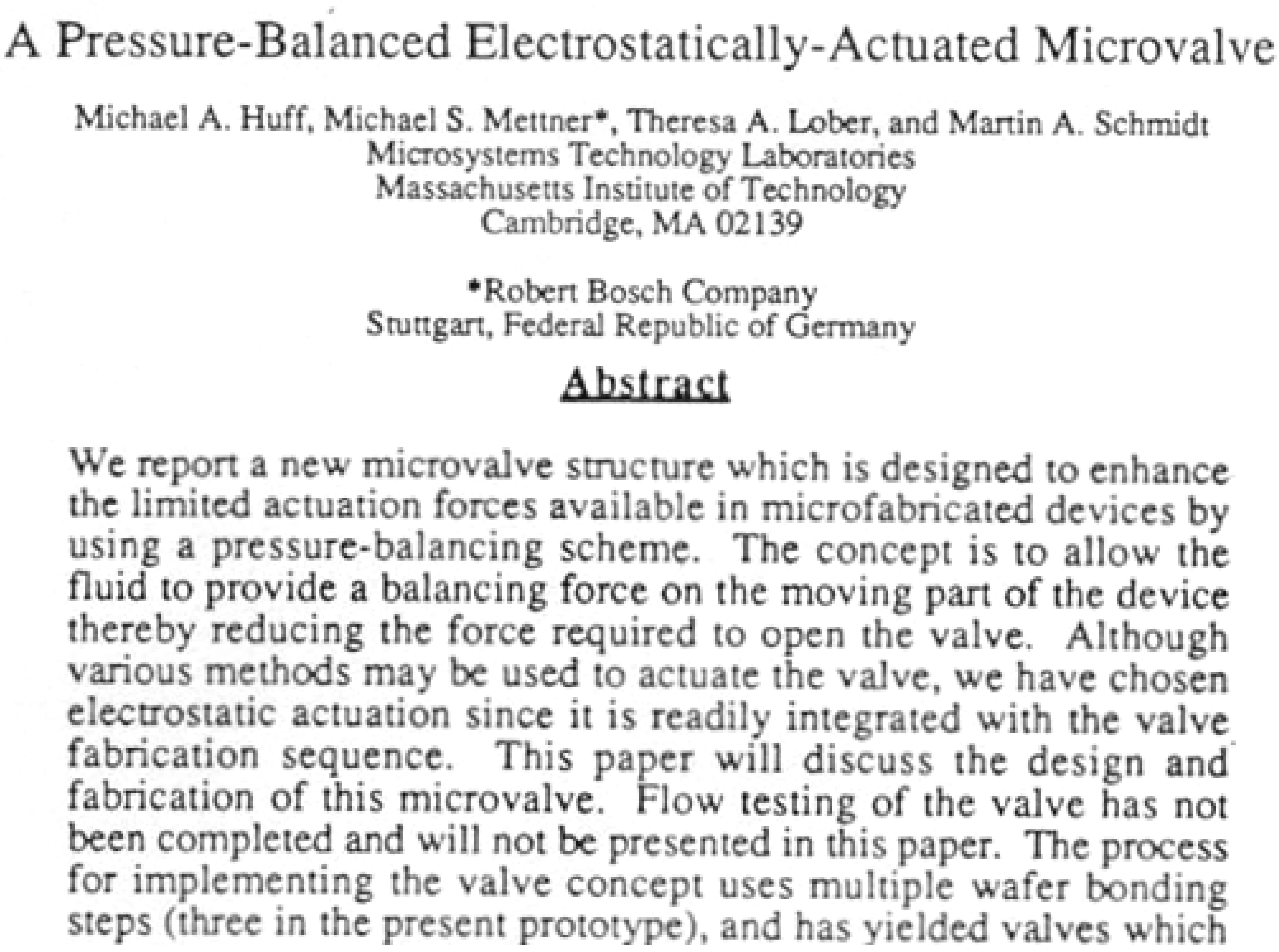


Figure 8. Flow modulation curves measured for the microvalve.

SUMMARY

An electrostatically actuated silicon microvalve which modulates a gas flow was fabricated and demonstrated. The microvalve is integrally fabricated on a single silicon wafer using surface and bulk micromachining and requires no final assembly. The microvalve operates against pressures of up to 114 mmHg and flows of up to 150 sccm with a 30 volt signal. The microvalve will hold back pressures of up to 760 mmHg. The valve may be operated in dc or pulse width modulated voltage modes. Investigation is continuing to characterize, model and improve the microvalve performance.

AN ELECTROSTATIC DIAPHRAGM VALVE



A Pressure-Balanced Electrostatically-Actuated Microvalve

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*Robert Bosch Company
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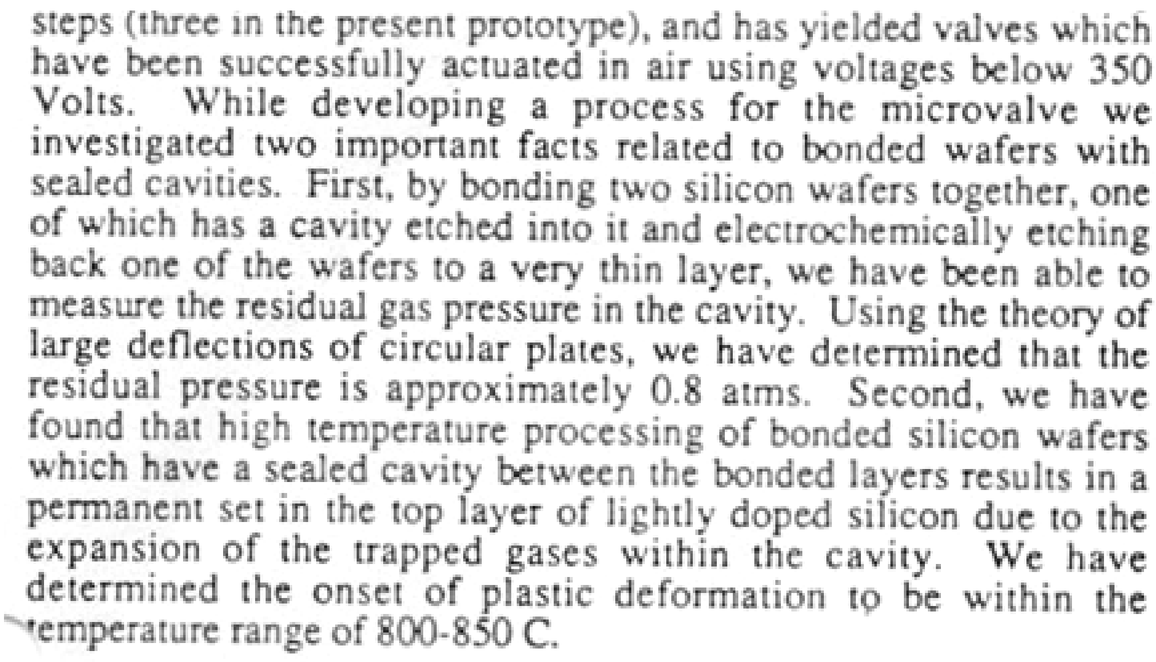
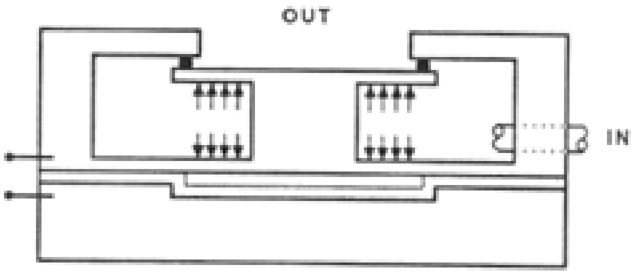
Abstract

We report a new microvalve structure which is designed to enhance the limited actuation forces available in microfabricated devices by using a pressure-balancing scheme. The concept is to allow the fluid to provide a balancing force on the moving part of the device thereby reducing the force required to open the valve. Although various methods may be used to actuate the valve, we have chosen electrostatic actuation since it is readily integrated with the valve fabrication sequence. This paper will discuss the design and fabrication of this microvalve. Flow testing of the valve has not been completed and will not be presented in this paper. The process for implementing the valve concept uses multiple wafer bonding steps (three in the present prototype), and has yielded valves which

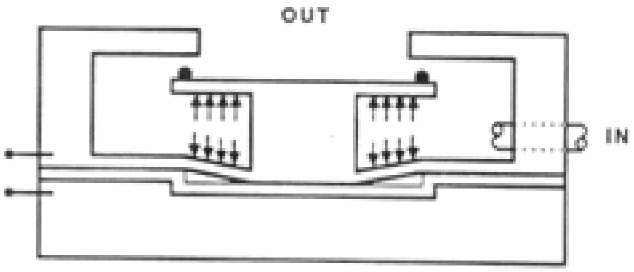
AN ELECTROSTATIC DIAPHRAGM VALVE



steps (three in the present prototype), and has yielded valves which have been successfully actuated in air using voltages below 350 Volts. While developing a process for the microvalve we investigated two important facts related to bonded wafers with sealed cavities. First, by bonding two silicon wafers together, one of which has a cavity etched into it and electrochemically etching back one of the wafers to a very thin layer, we have been able to measure the residual gas pressure in the cavity. Using the theory of large deflections of circular plates, we have determined that the residual pressure is approximately 0.8 atms. Second, we have found that high temperature processing of bonded silicon wafers which have a sealed cavity between the bonded layers results in a permanent set in the top layer of lightly doped silicon due to the expansion of the trapped gases within the cavity. We have determined the onset of plastic deformation to be within the temperature range of 800-850 C.



VALVE CLOSED



VALVE OPEN

AN ELECTROSTATIC DIAPHRAGM VALVE

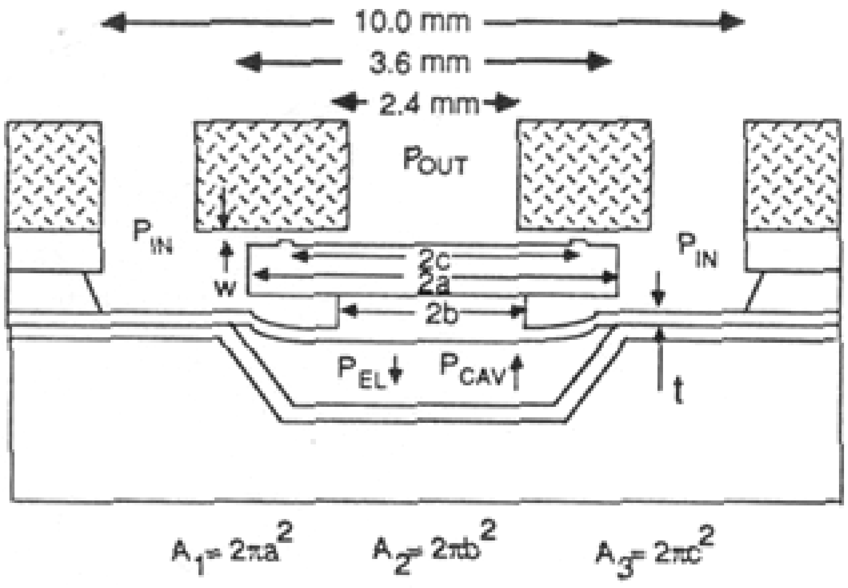


Figure 2. Valve Dimensions

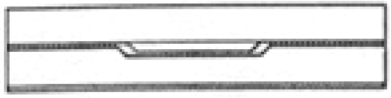
Fabrication

The process for implementing the valve concept uses three wafer bonding steps and does not yet have the sealing ring as shown in Figure 2. The fabrication sequence (Figure 3) of the valve begins with a n-type <100> 0.5-2.0 ohm-cm 4-inch silicon wafer. The wafer is placed in a phosphorus diffusion furnace at 925 C for 1.5 hours in order to highly dope the surface. This step is done to ensure that good electrical contact can be made in order to actuate the valve. After a one hour drive-in at 950 C, the wafer is stripped of the phosphorous-doped glass and a 1000 Å thermal oxide is grown. After the masking oxide is patterned the wafer is placed in 20% KOH at 56 C for approximately 22 minutes thereby etching circular recessed electrodes 5 µm deep and 3.6 mm in diameter, Figure 2a. The masking oxide is then stripped and a thermal oxide, 1.6 µm-thick, is grown on the wafer. This thick layer of silicon dioxide acts as the dielectric isolation during electrostatic actuation and will also serve to protect the handle wafer from the subsequent silicon etching steps.

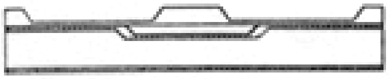
A second 4-inch wafer, <100> p-type 10-20 ohm-cm, is thermally bonded to the front side of the first wafer, Figure 2b. Prior to bonding, the two wafers are cleaned using a standard pre-oxidation clean and then hydrated by immersion into a 3:1, sulfuric acid:hydrogen peroxide solution. After a spin rinse and dry, the polished surfaces of the wafers are physically placed into intimate contact. Using an infrared inspection system, the wafers are examined for voids. Assuming the bond is void-free, the composite two-wafer structure is placed into a dry oxidation furnace for one hour at 1000 C to complete the bond. Once removed from the

AN ELECTROSTATIC DIAPHRAGM VALVE

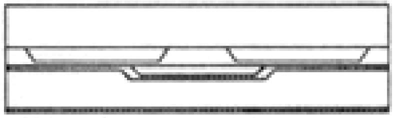
(a) Etch Trench in Silicon Substrate



(b) Grow Oxide and Bond Wafer

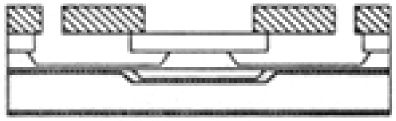


(c) Etch-back and Pattern Wafer #2



(d) Bond Wafer #3

(e) Pattern Wafer #3



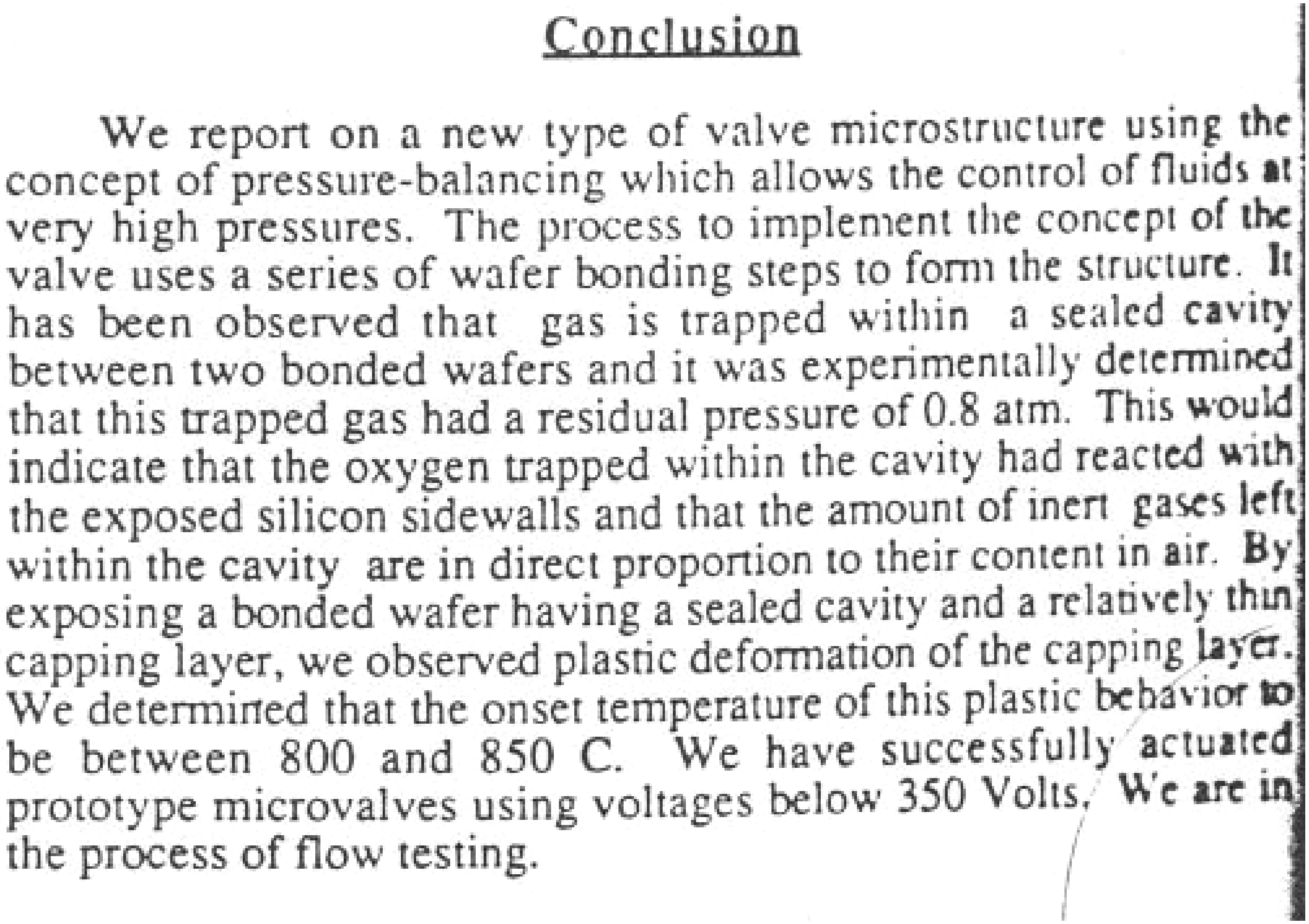
(f) Packaged Valve

furnace, the bonded wafers are inspected again using the infrared inspection system.

The bonded wafers are then placed in a 20% KOH solution at 56 C for approximately 23.5 hours and the second wafer is etched back to a resulting thickness of 75 µm. The surface of the etched back wafer is then mechanically polished to a mirror-smooth finish. The resulting thickness of the second silicon wafer is 50 µm. A masking oxide, (LTO), 5000 Å thick is deposited onto the just polished surface and subsequently patterned. The wafers is then tched using a 20 % KOH solution at 56 C for approximately 1.5 ours forming the base of the valve, Figure 2c. After the masking oxide is stripped a third 4-inch <100> silicon wafer, p-type 10-20 ohm-cm, is thermally bonded to the polished surface of the second wafer, Figure 2d. The bonding is done in exactly the same way as described above. After bonding, the composite structure is inspected using the infrared inspection system. Figure 4 is a thermal print-out of the infrared inspection system clearly indicating the plunger base bonded to the third wafer.

The third wafer is etched back in a 20% KOH solution at 56 C to a resultant thickness of 75 µm. A 5000 Å-thick oxide is deposited onto the third wafer surface using either LTO or an ACVD oxide. Subsequently, the wafer is patterned and etched in a 20% KOH solution at 56 C forming the top layer and releasing the valve, Figure 2e. The complete wafer is sawed into individual valves, which are then packaged using a capping glass plate which contains inlet and outlet ports, Figure 2f.

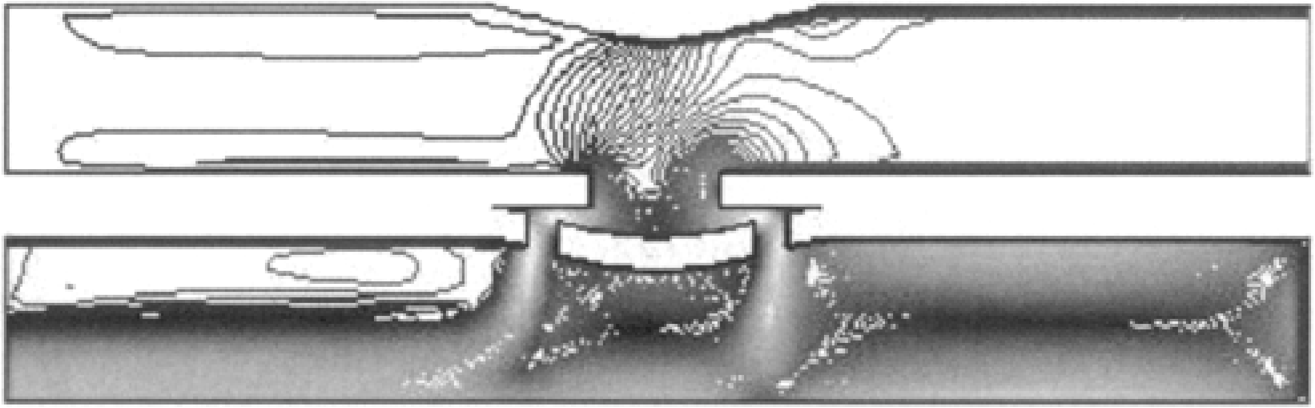
AN ELECTROSTATIC DIAPHRAGM VALVE

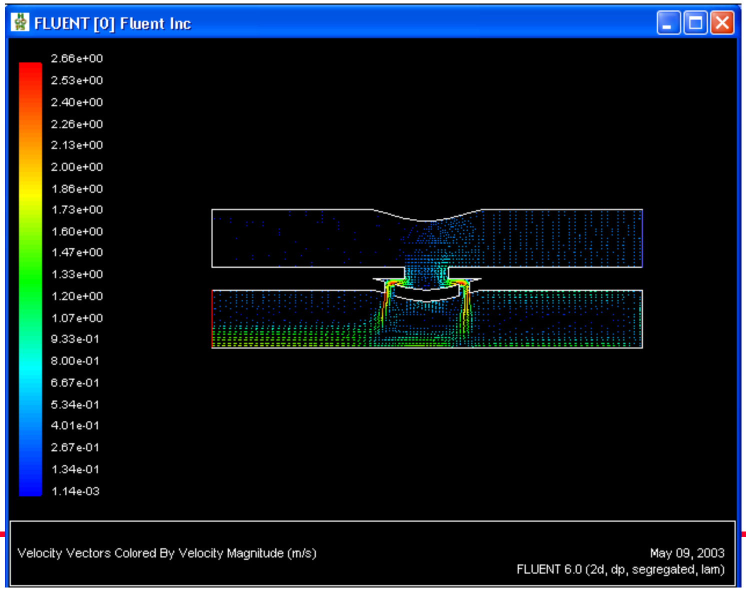


Conclusion

We report on a new type of valve microstructure using the concept of pressure-balancing which allows the control of fluids at very high pressures. The process to implement the concept of the valve uses a series of wafer bonding steps to form the structure. It has been observed that gas is trapped within a sealed cavity between two bonded wafers and it was experimentally determined that this trapped gas had a residual pressure of 0.8 atm. This would indicate that the oxygen trapped within the cavity had reacted with the exposed silicon sidewalls and that the amount of inert gases left within the cavity are in direct proportion to their content in air. By exposing a bonded wafer having a sealed cavity and a relatively thin capping layer, we observed plastic deformation of the capping layer. We determined that the onset temperature of this plastic behavior to be between 800 and 850 C. We have successfully actuated prototype microvalves using voltages below 350 Volts. We are in the process of flow testing.

VALVE DESIGN AND SIMULATION



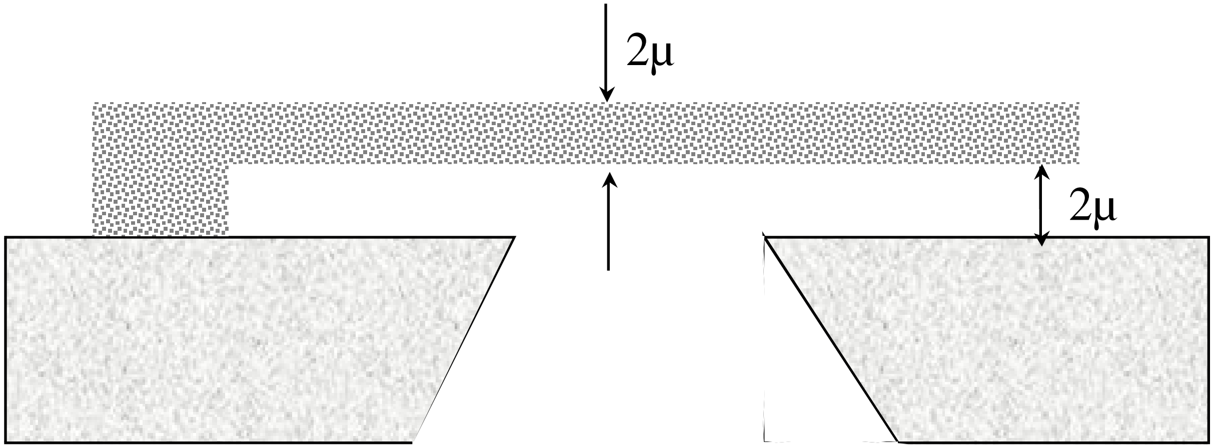


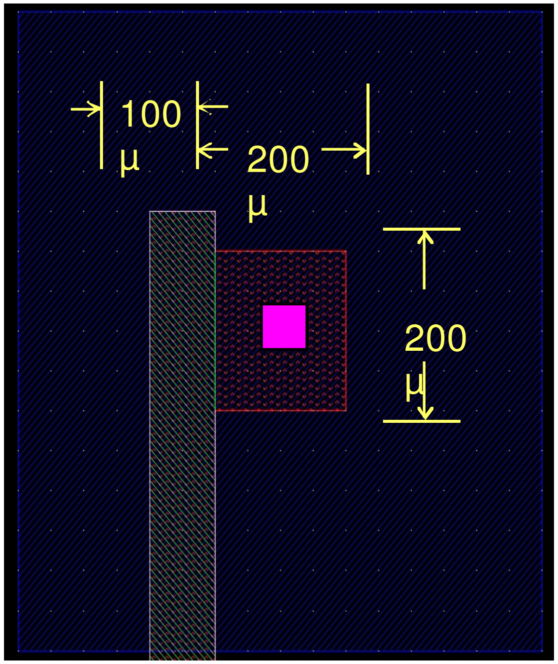
Velocity Vectors Colored By Velocity Magnitude (m/s)

May 09, 2003
FLUENT 6.0 (2d, dp, segregated, lam)

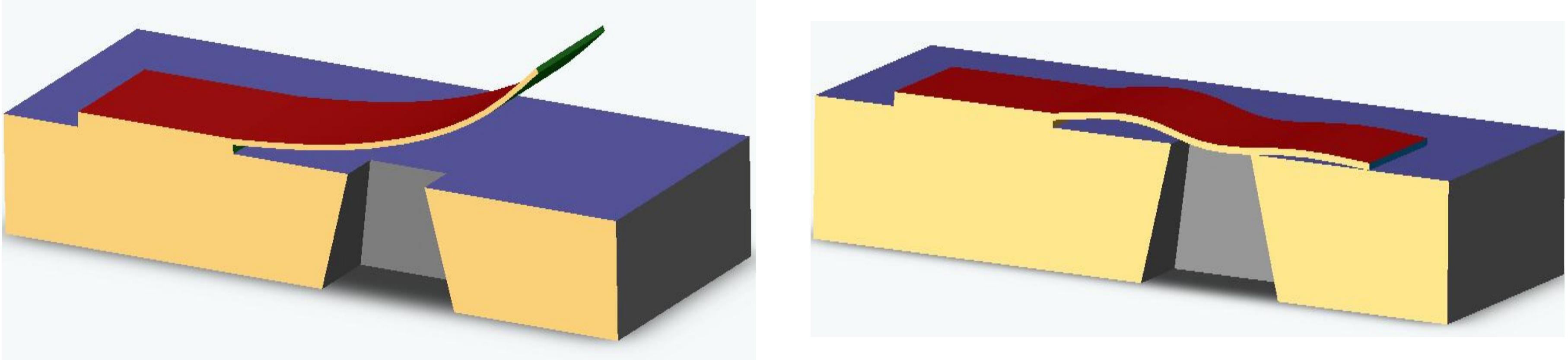
Greg Schallert – 2003
Fluent Simulation

JERMAINE WHITE CHECK VALVE



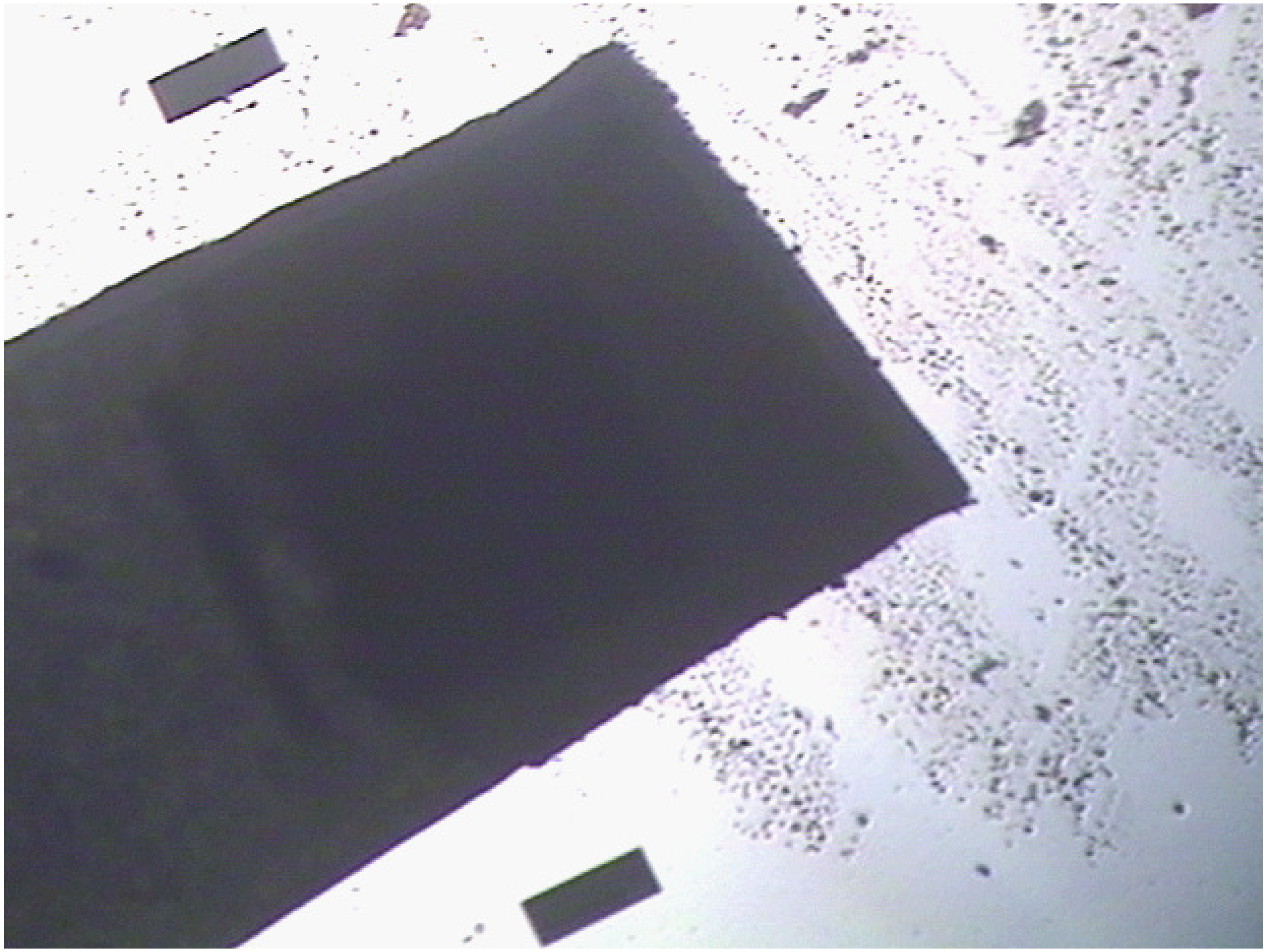


CHECK VALVE THEORY OF OPERATION



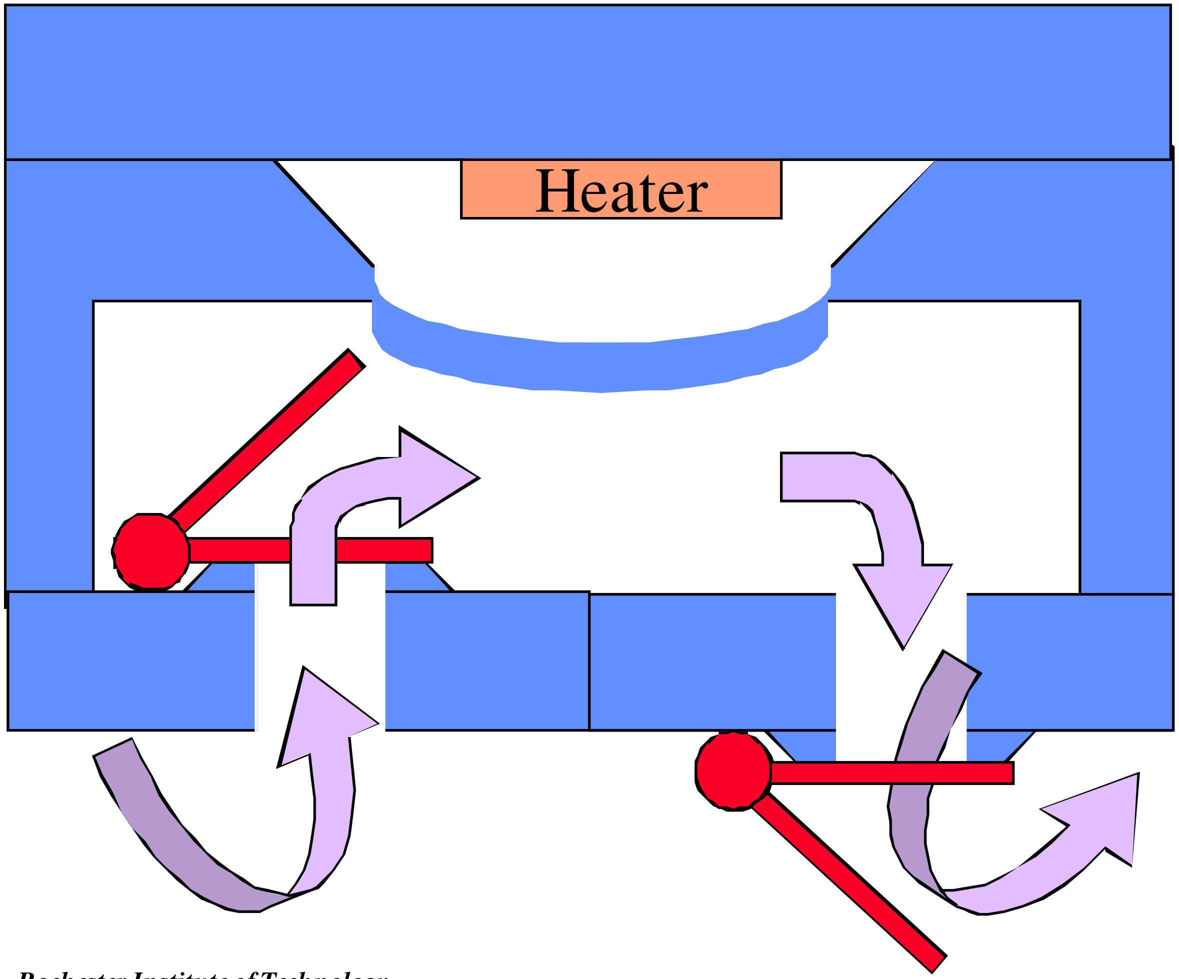
- When the backside pressure is greater, the flexible flap will bend up and allow airflow.
- When the front side pressure is greater, the flap bends down and occludes the hole thus preventing airflow.

MOVIE OF CHECK VALVE OPERATING



MOVIE OF CHECK VALVE OPERATING

DIAPHRAGM PUMP



PERISTALTIC PUMP

THERMAL ACTIVATED DIAPHRAGM PUMP

A Thermopneumatic Micropump Based on Micro-engineering Techniques

F. C. M. VAN DE POL, H. T. G. VAN LINTEL, M. ELWENSPOEK and J. H. J. FLUITMAN

University of Twente, Department of Electrical Engineering, P.O. Box 217, 7500 AE Enschede (The Netherlands)

Reprinted with permission from *Transducers '89, Proceedings of the 5th International Conference on Solid-State Sensors and Actuators and Eurosensors III.* F. Van de Pol, H. Van Lintel, M. Elwenspoek, and J. Pluitman, "A Thermopneumatic Micropump Based on Micro-Engineering Techniques," Vol. 2, pp. 198-202, June 1990. © Elsevier Sequoia.

Abstract

The design, working principle and realization of an electro-thermopneumatic liquid pump based on micro-engineering techniques are described. The pump, which is of the reciprocating displacement type, comprises a pump chamber, a thin silicon pump membrane and two silicon check valves to direct the flow. The dynamic pressure of an amount of gas contained in a cavity, controlled by resistive heating, actuates the pump membrane. The cavity, chambers, channels and valves are realized in silicon wafers by wet chemical etching. Experimental results are presented. Maximum yield and built-up pressure equal 34 μl/min and 0.05 atm, at a supply voltage of 6 V. Results of simulations show good agreement with the actual dynamic behaviour of the pump.

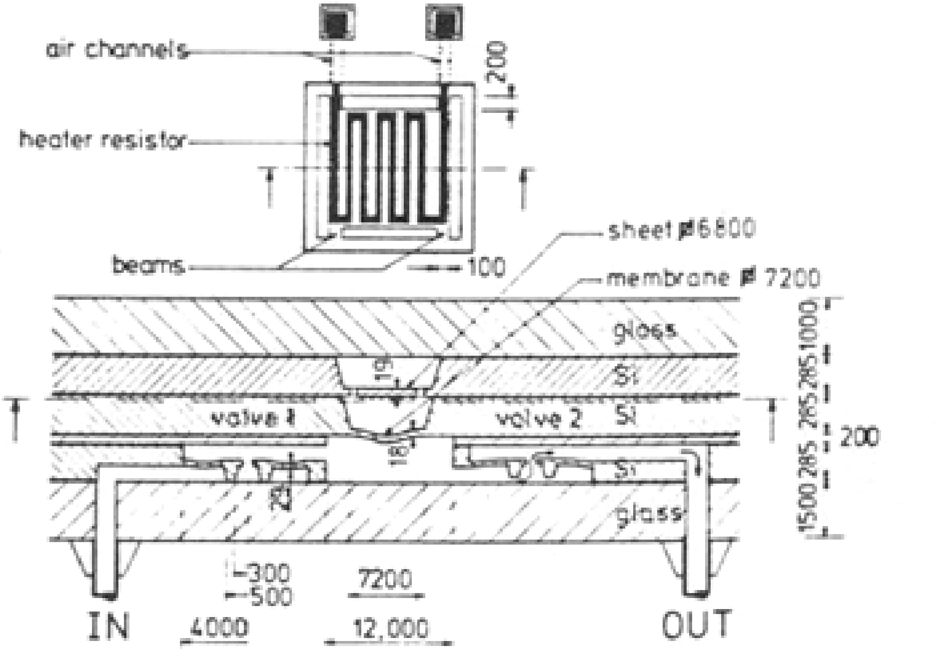
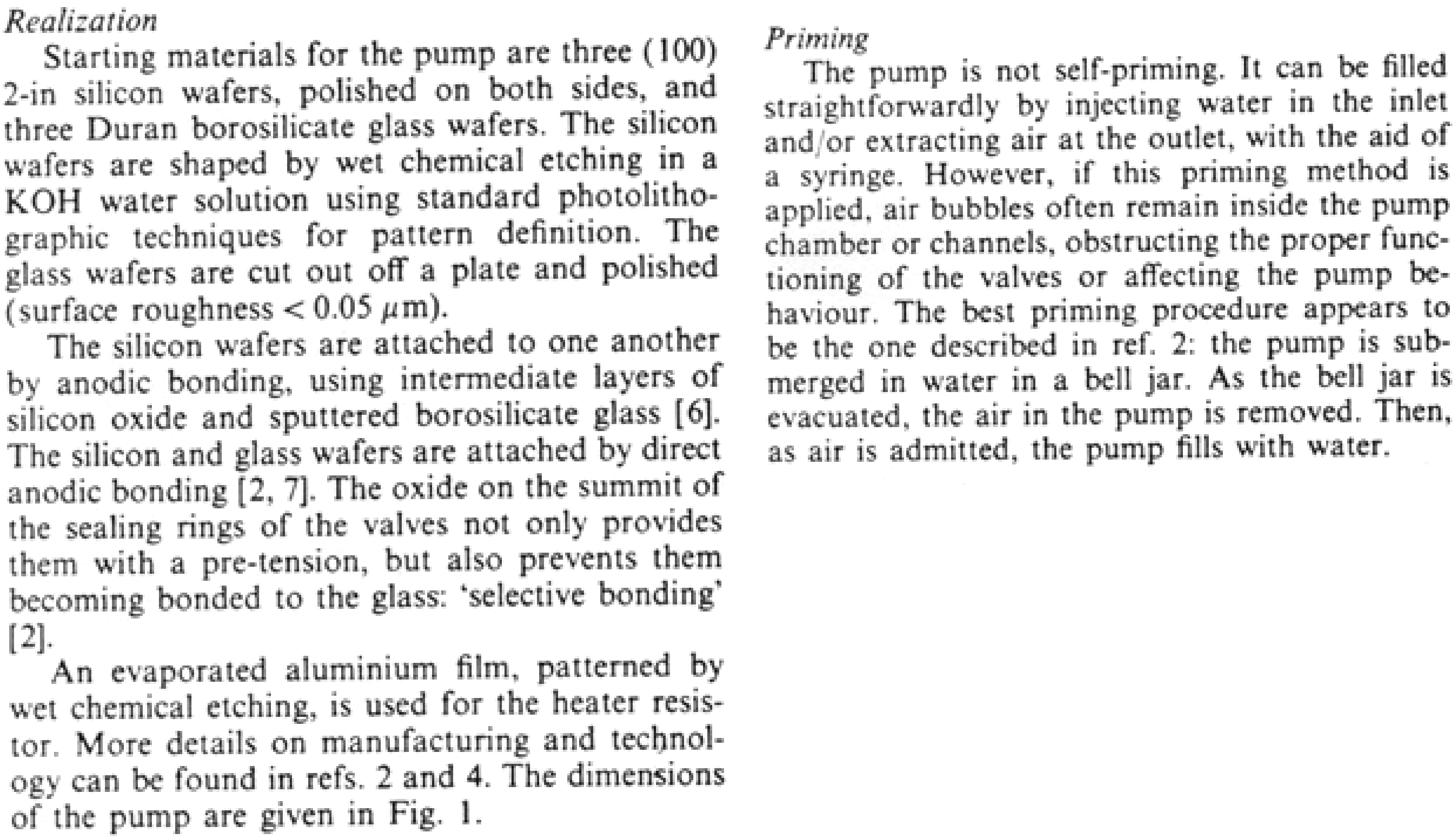


Fig. 1. Cross-sectional views of the pump (dimensions in μm).

THERMAL ACTIVATED DIAPHRAGM PUMP



Realization

Starting materials for the pump are three (100) 2-in silicon wafers, polished on both sides, and three Duran borosilicate glass wafers. The silicon wafers are shaped by wet chemical etching in a KOH water solution using standard photolithographic techniques for pattern definition. The glass wafers are cut out off a plate and polished (surface roughness < 0.05 μm).

The silicon wafers are attached to one another by anodic bonding, using intermediate layers of silicon oxide and sputtered borosilicate glass [6]. The silicon and glass wafers are attached by direct anodic bonding [2, 7]. The oxide on the summit of the sealing rings of the valves not only provides them with a pre-tension, but also prevents them becoming bonded to the glass: 'selective bonding' [2].

An evaporated aluminium film, patterned by wet chemical etching, is used for the heater resistor. More details on manufacturing and technology can be found in refs. 2 and 4. The dimensions of the pump are given in Fig. 1.

Priming

The pump is not self-priming. It can be filled straightforwardly by injecting water in the inlet and/or extracting air at the outlet, with the aid of a syringe. However, if this priming method is applied, air bubbles often remain inside the pump chamber or channels, obstructing the proper functioning of the valves or affecting the pump behaviour. The best priming procedure appears to be the one described in ref. 2: the pump is submerged in water in a bell jar. As the bell jar is evacuated, the air in the pump is removed. Then, as air is admitted, the pump fills with water.

THERMAL ACTIVATED DIAPHRAGM PUMP

Measurements

In Fig. 2, the measurement set-up is depicted. A pulsed d.c. voltage, variable in height and frequency, is applied to the bonding pads connected to the heater resistor. Pumped volume and yield are measured with the aid of a glass capillary tube and a stopwatch. Specific pressures at the inlet and outlet of the pump are established by adjusting h_{out} and h_{in}.

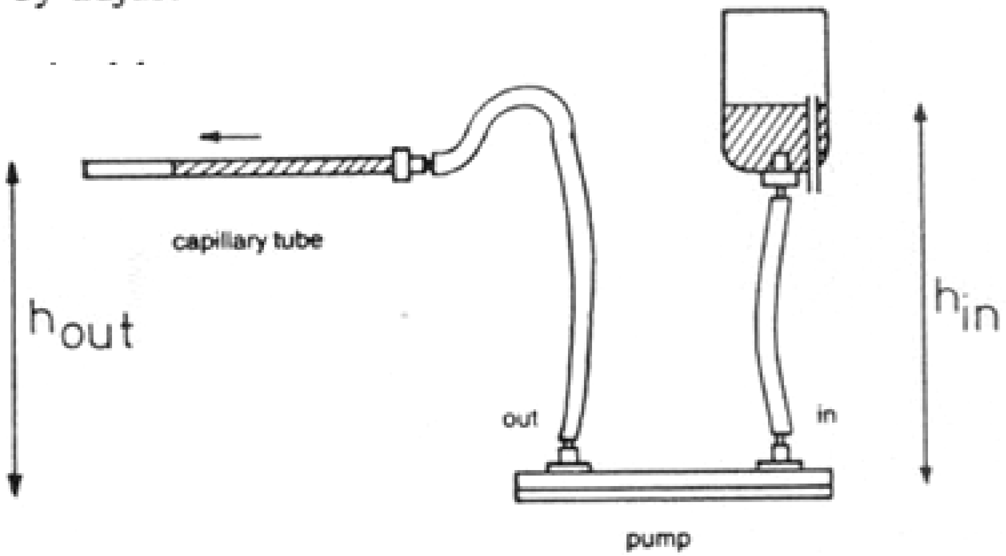


Fig. 2. Measurement set-up.

THERMAL ACTIVATED DIAPHRAGM PUMP

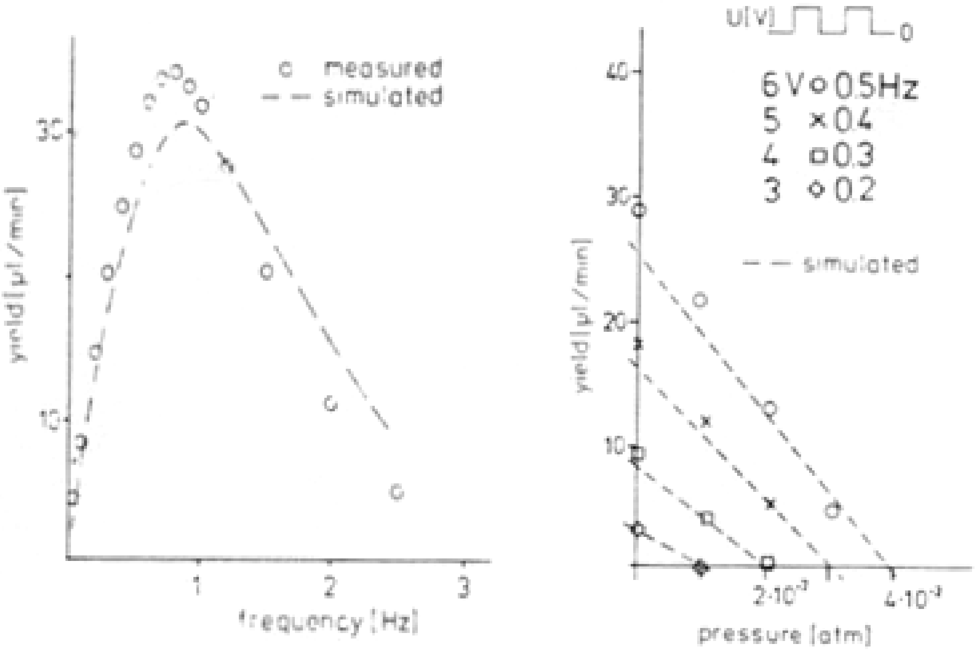


Fig. 3. (a) Pump yield as a function of pump frequency for an applied voltage of 6 V at zero back pressure (outlet minus inlet pressure). (b) Pump yield as a function of back pressure, applied voltage and pump frequency.

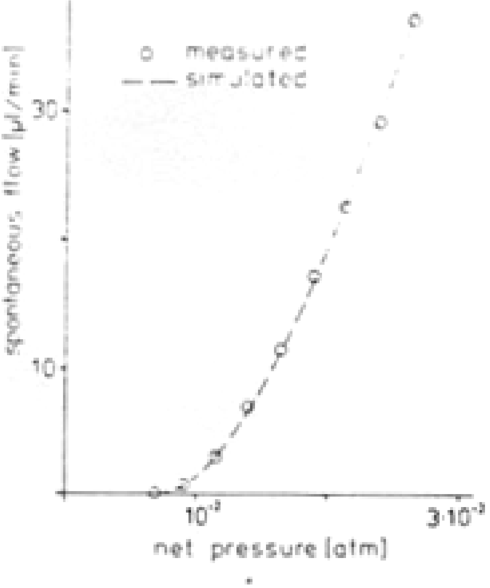
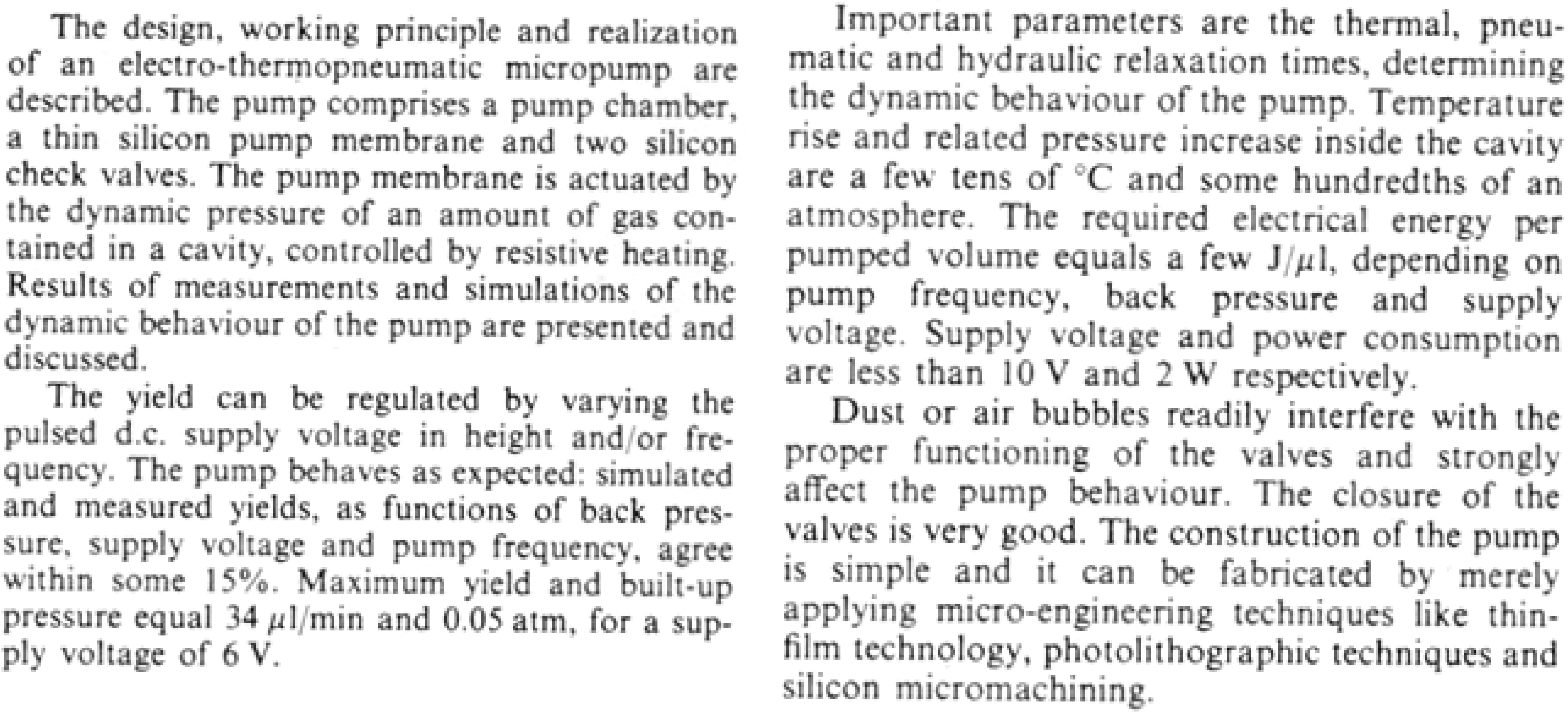


Fig. 4. Measured and simulated spontaneous flow vs. net pressure (inlet minus outlet pressure).

THERMAL ACTIVATED DIAPHRAGM PUMP

Conclusion:



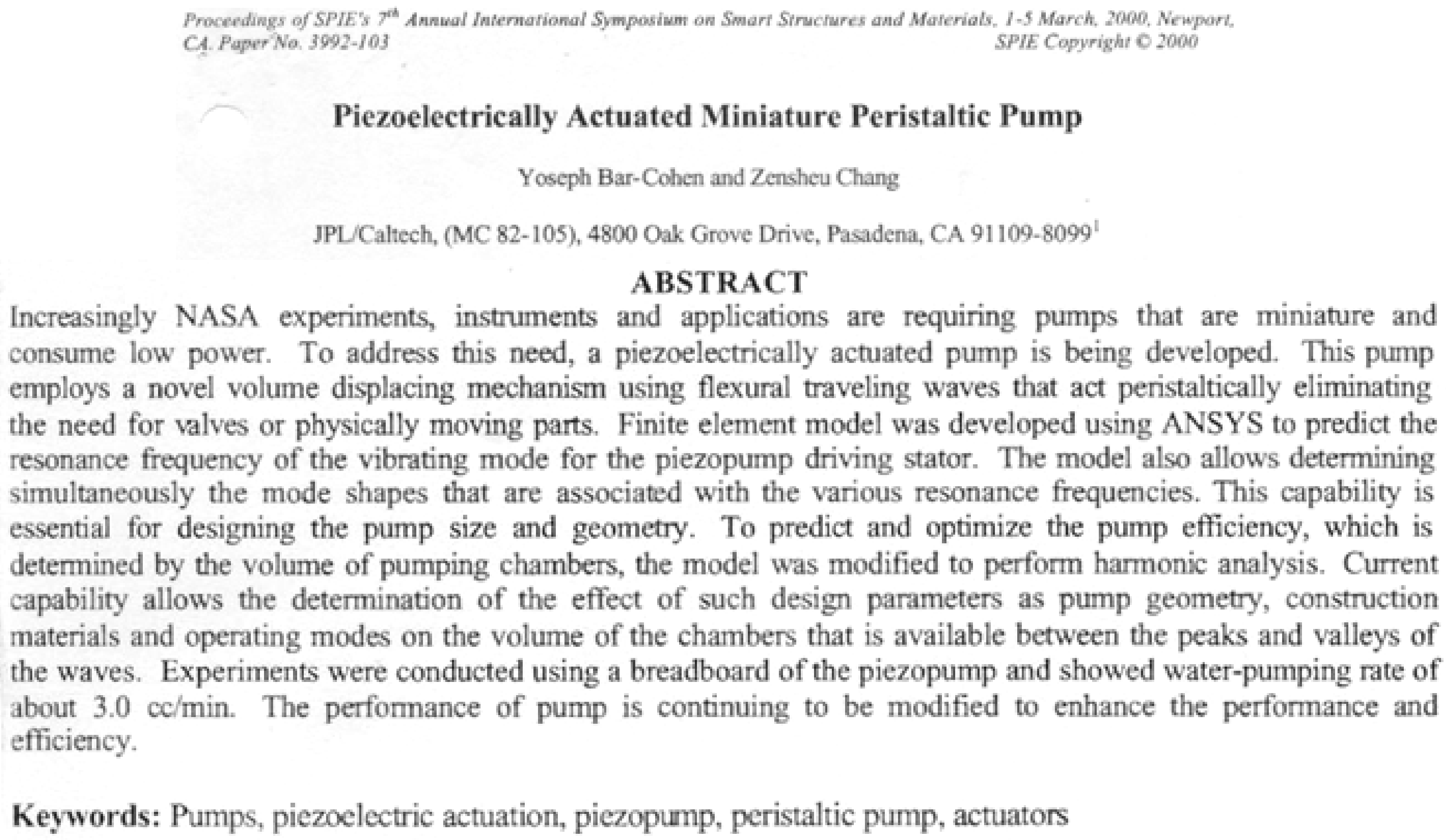
The design, working principle and realization of an electro-thermopneumatic micropump are described. The pump comprises a pump chamber, a thin silicon pump membrane and two silicon check valves. The pump membrane is actuated by the dynamic pressure of an amount of gas contained in a cavity, controlled by resistive heating. Results of measurements and simulations of the dynamic behaviour of the pump are presented and discussed.

The yield can be regulated by varying the pulsed d.c. supply voltage in height and/or frequency. The pump behaves as expected: simulated and measured yields, as functions of back pressure, supply voltage and pump frequency, agree within some 15%. Maximum yield and built-up pressure equal 34 μl/min and 0.05 atm, for a supply voltage of 6 V.

Important parameters are the thermal, pneumatic and hydraulic relaxation times, determining the dynamic behaviour of the pump. Temperature rise and related pressure increase inside the cavity are a few tens of °C and some hundredths of an atmosphere. The required electrical energy per pumped volume equals a few J/μl, depending on pump frequency, back pressure and supply voltage. Supply voltage and power consumption are less than 10 V and 2 W respectively.

Dust or air bubbles readily interfere with the proper functioning of the valves and strongly affect the pump behaviour. The closure of the valves is very good. The construction of the pump is simple and it can be fabricated by merely applying micro-engineering techniques like thin-film technology, photolithographic techniques and silicon micromachining.

PIEZOELECTRIC ACTIVATED PERISTALTIC PUMP



Proceedings of SPIE's 7th Annual International Symposium on Smart Structures and Materials, 1-5 March, 2000, Newport, CA. Paper No. 3992-103

Piezoelectrically Actuated Miniature Peristaltic Pump

Yoseph Bar-Cohen and Zensheu Chang

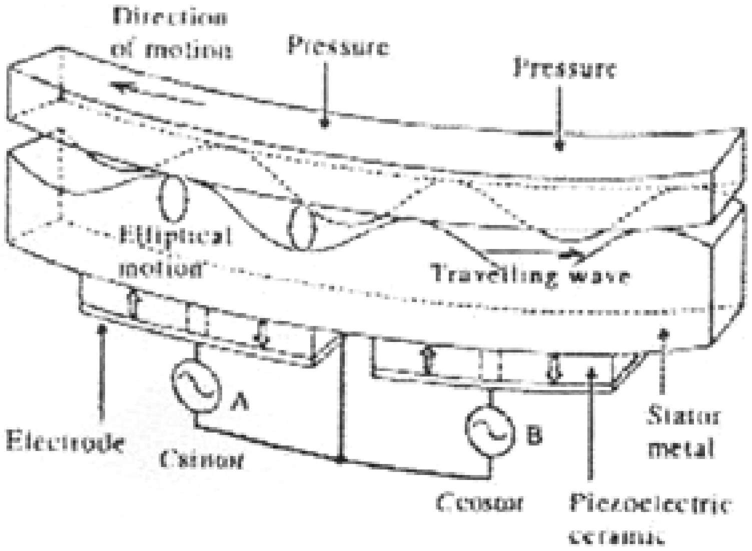
JPL/Caltech, (MC 82-105), 4800 Oak Grove Drive, Pasadena, CA 91109-8099[1]

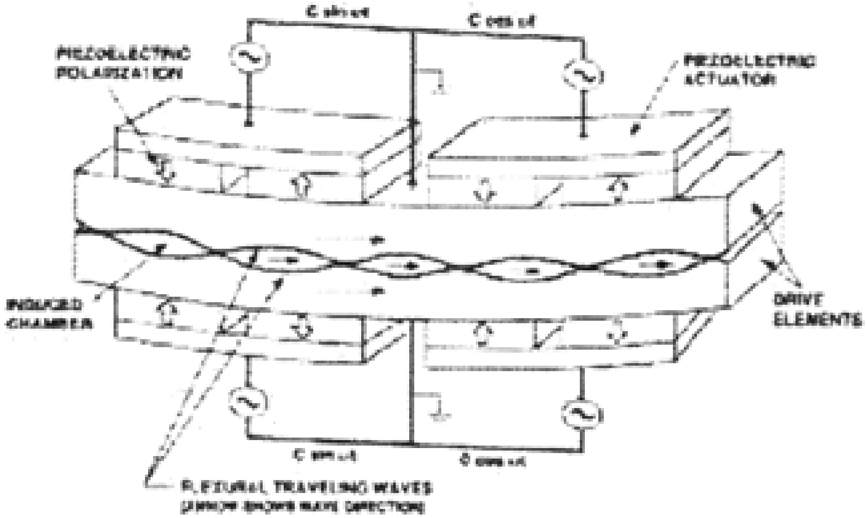
ABSTRACT

Increasingly NASA experiments, instruments and applications are requiring pumps that are miniature and consume low power. To address this need, a piezoelectrically actuated pump is being developed. This pump employs a novel volume displacing mechanism using flexural traveling waves that act peristaltically eliminating the need for valves or physically moving parts. Finite element model was developed using ANSYS to predict the resonance frequency of the vibrating mode for the piezopump driving stator. The model also allows determining simultaneously the mode shapes that are associated with the various resonance frequencies. This capability is essential for designing the pump size and geometry. To predict and optimize the pump efficiency, which is determined by the volume of pumping chambers, the model was modified to perform harmonic analysis. Current capability allows the determination of the effect of such design parameters as pump geometry, construction materials and operating modes on the volume of the chambers that is available between the peaks and valleys of the waves. Experiments were conducted using a breadboard of the piezopump and showed water-pumping rate of about 3.0 cc/min. The performance of pump is continuing to be modified to enhance the performance and efficiency.

Keywords: Pumps, piezoelectric actuation, piezopump, peristaltic pump, actuators

PIEZOELECTRIC ACTIVATED PERISTALTIC PUMP





PIEZOELECTRIC ACTIVATED PERISTALTIC PUMP

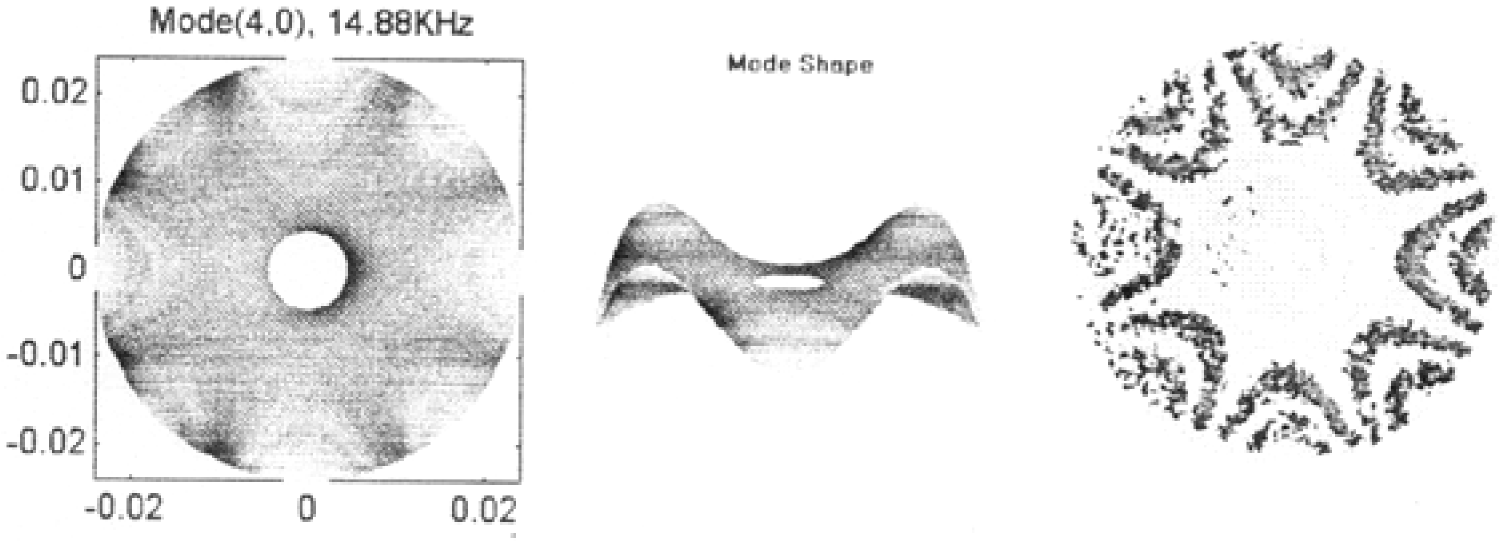


FIGURE 3: A view of the theoretical prediction of the frequency response of a stator that is driven by 4-mode piezoelectric actuators (left) and the experimental corroboration using interferometry.

PIEZOELECTRIC ACTIVATED PERISTALTIC PUMP

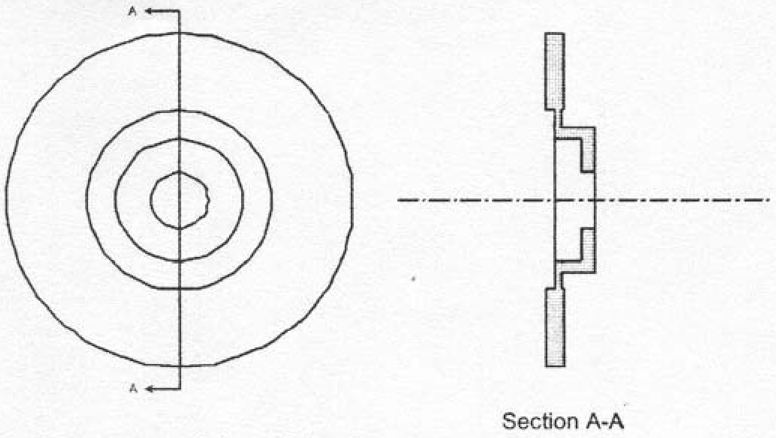


Figure 7: Metal ring of the piezo pump.

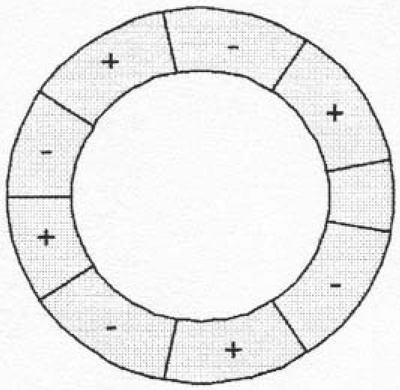


Figure 8: A piezoelectric ring designed for 4-wave mode.

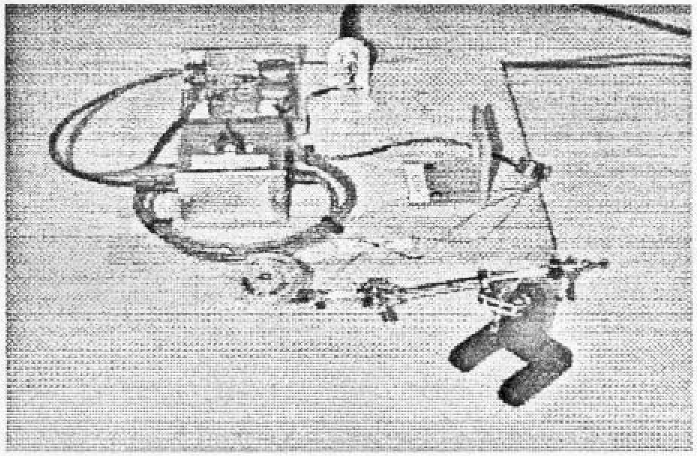


Figure 9: Piezopump brassboard system.

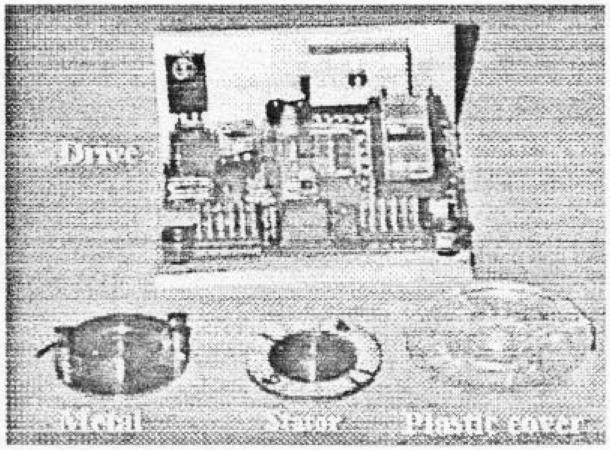
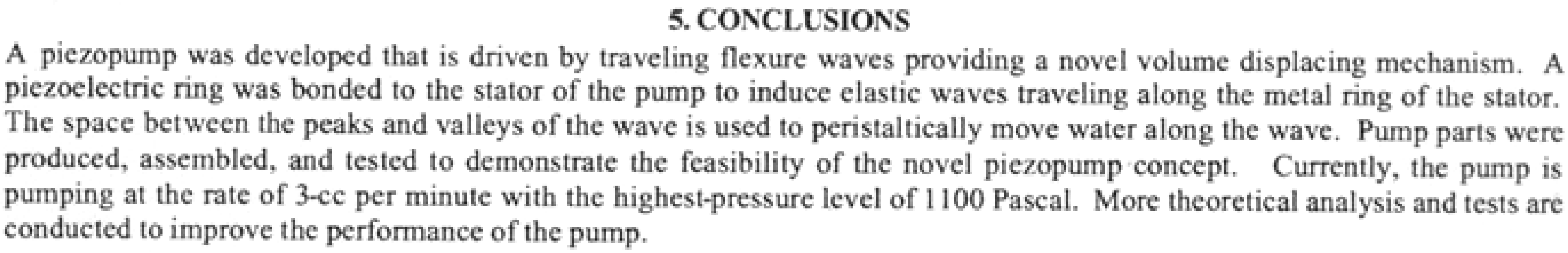


Figure 10: Components of a piezopump.

PIEZOELECTRIC ACTIVATED PERISTALTIC PUMP



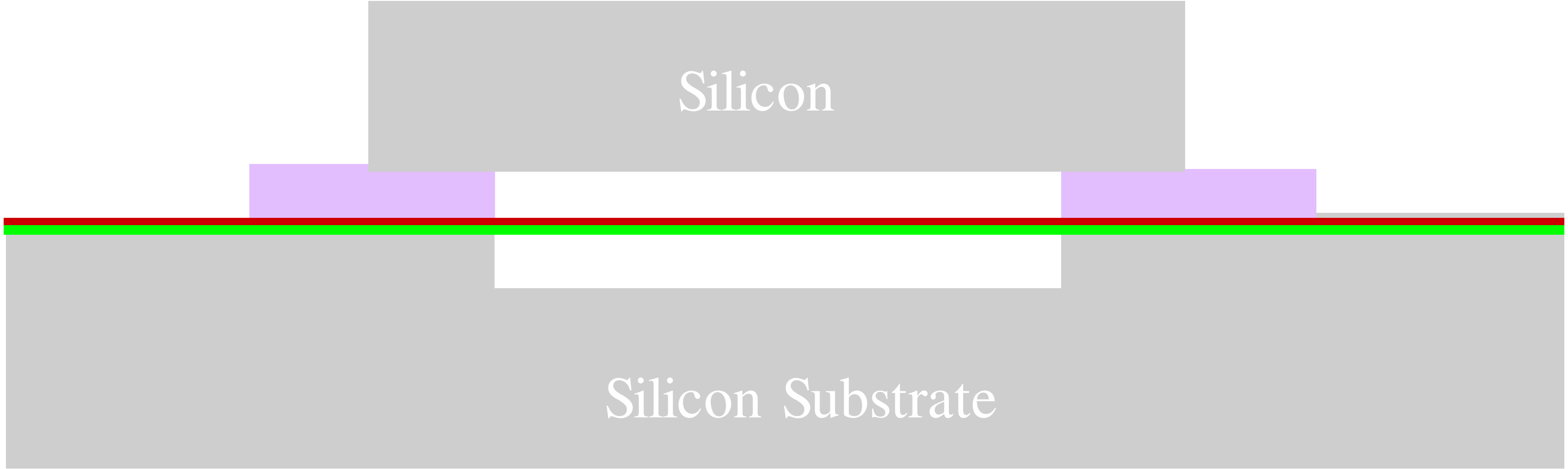
5. CONCLUSIONS

A piezopump was developed that is driven by traveling flexure waves providing a novel volume displacing mechanism. A piezoelectric ring was bonded to the stator of the pump to induce elastic waves traveling along the metal ring of the stator. The space between the peaks and valleys of the wave is used to peristaltically move water along the wave. Pump parts were produced, assembled, and tested to demonstrate the feasibility of the novel piezopump concept. Currently, the pump is pumping at the rate of 3-cc per minute with the highest-pressure level of 1100 Pascal. More theoretical analysis and tests are conducted to improve the performance of the pump.

Flow = 3 cc/min

Pressure = 1100 Pascal = 0.16 psi

THERMAL ACTUATED PERISTALTIC PUMP

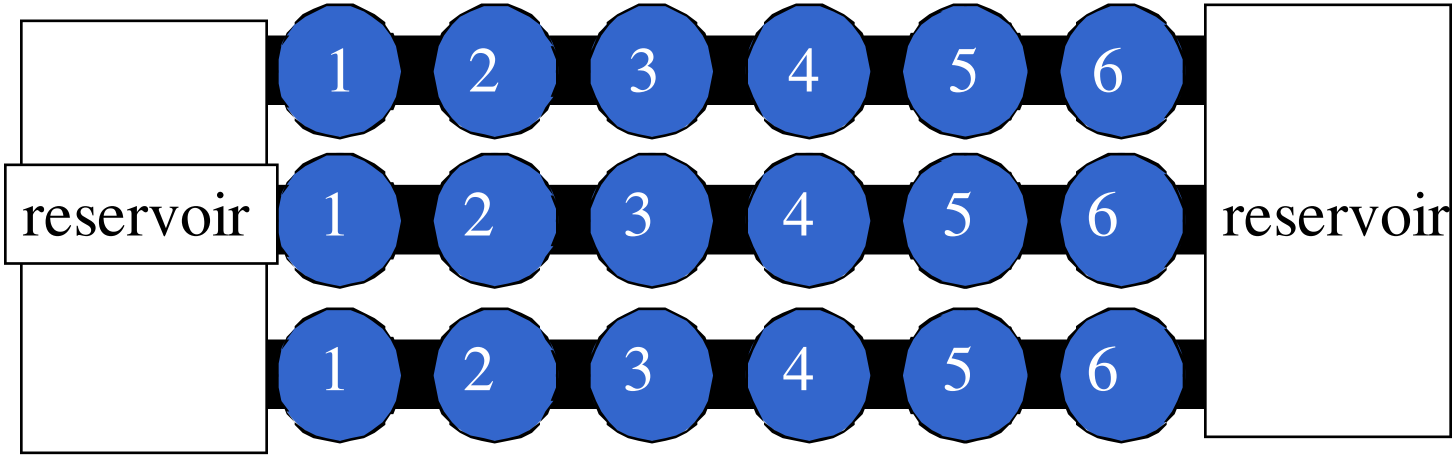


🟪 Insulating material

🟥 Thin Film Heater

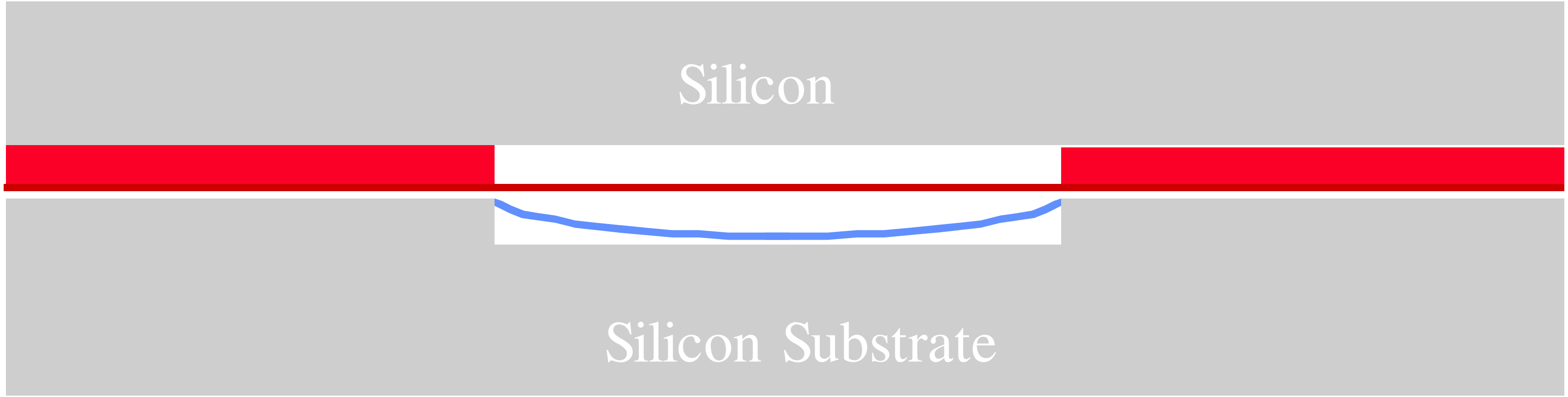
🟩 80 µm diaphragm (watch glass)

THERMAL ACTUATED PERISTALTIC PUMP



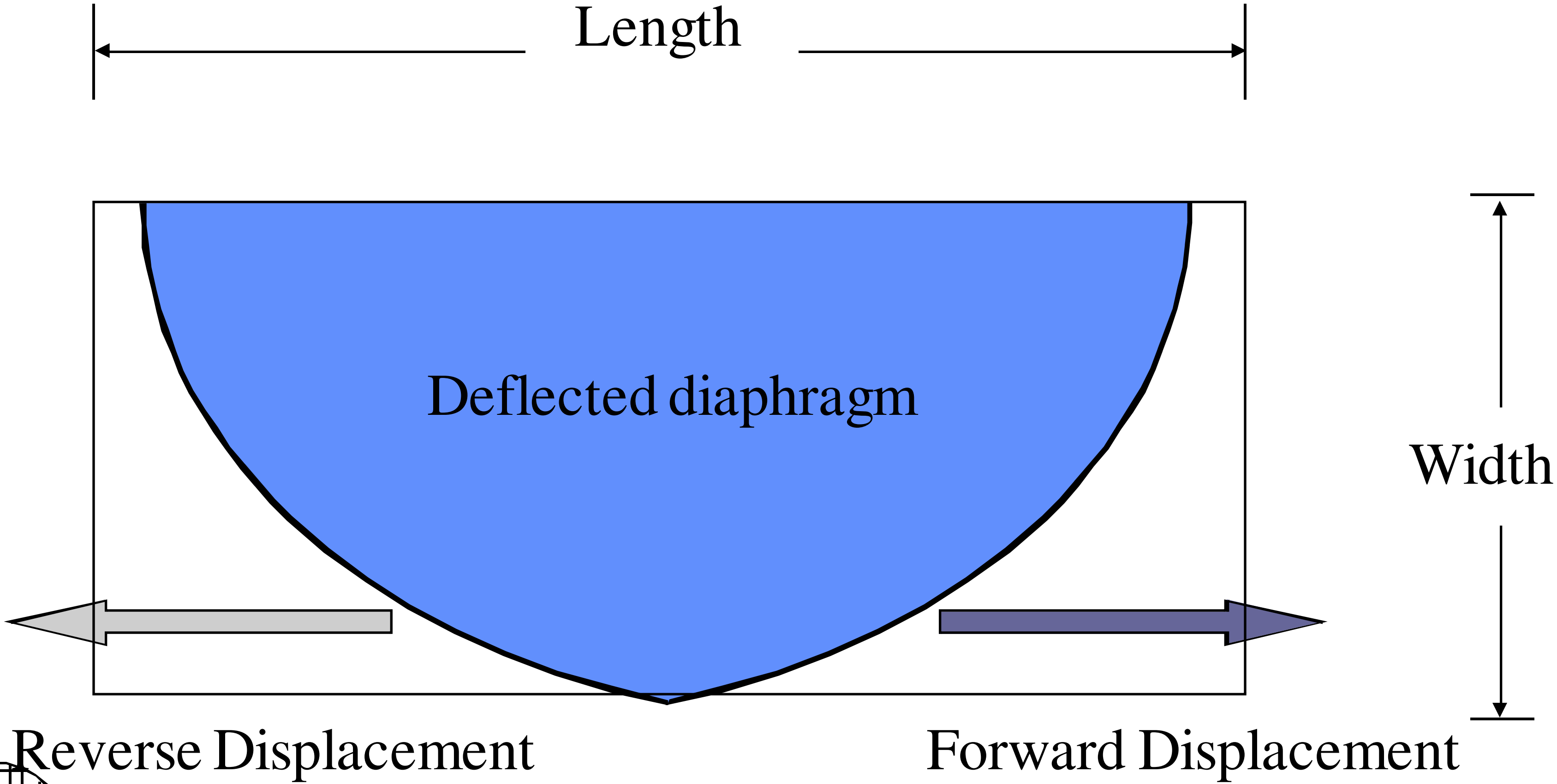
- Sequentially activating the pumps 1- 6 will advance the fluid
- Cycling pumping system gives desired flow rate [picoL/sec]
- Additional channels can be added in increase flow rate further

THERMAL ACTUATED PERISTALTIC PUMP



- The resistive heating element heats the cavity
- The cavity pressure rises till the watch glass deflects downward since p/T = constant (want 10 psi activation pressure)
- The deflection results in volume displacement in the etched channel

THERMAL ACTUATED PERISTALTIC PUMP



THERMAL ACTUATED PERISTALTIC PUMP

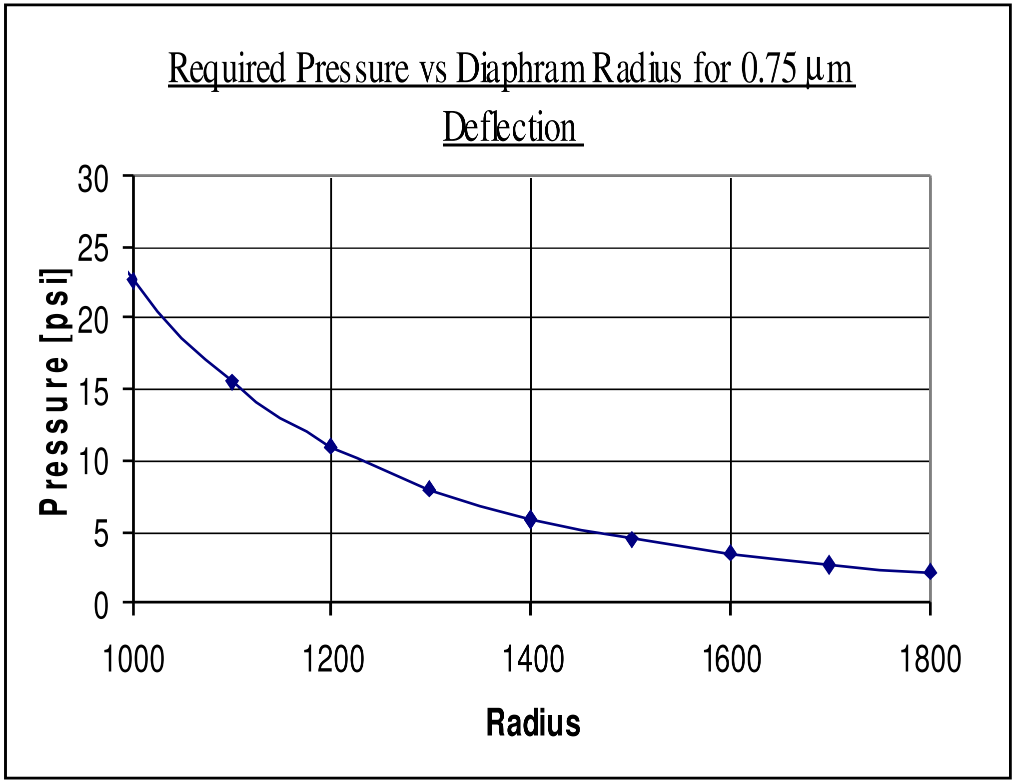
$$y = \frac{(249.979)PR^4[(1/v)^2 - 1]}{E(1/v)^2\delta^3}$$

y = deflection [µm]
P = pressure [mm hg]
R = diaphragm radius [µm]
v = Poisson’s ratio [-]
Y = Young’s Modulus [dyne/cm^2]
δ = diaphragm thickness [µm]

THERMAL ACTUATED PERISTALTIC PUMP

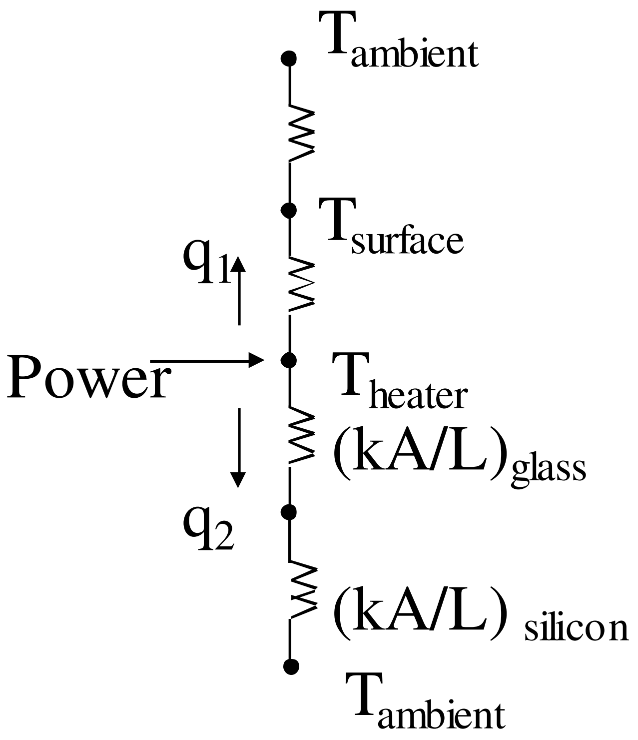
Required Pressure vs Diaphragm Radius for 0.75 µm deflection

- v = 0.206 [-]
- y = 0.75 µm
- Y = 7.30E11 dyne/cm²
- δ = 80 µm
- P = 517.149 mm Hg (10 psi)
- R = 1226.932983 µm



THERMAL ACTUATED PERISTALTIC PUMP

Thermal Design Calculations



$$(\cancelto{0}{q_{in}} - q_{out}) + \cancelto{0}{q_{gen}} = q_{stored}$$

$$q_{gen} = \cancelto{\sim 0}{q_1} + q_2$$

$$q_{gen} = q_2$$

$$q_2 = \frac{T_{heater} - T_{ambient}}{(kA/L)_{glass} + (kA/L)_{silicon}}$$

$$= 20\text{ mW}$$

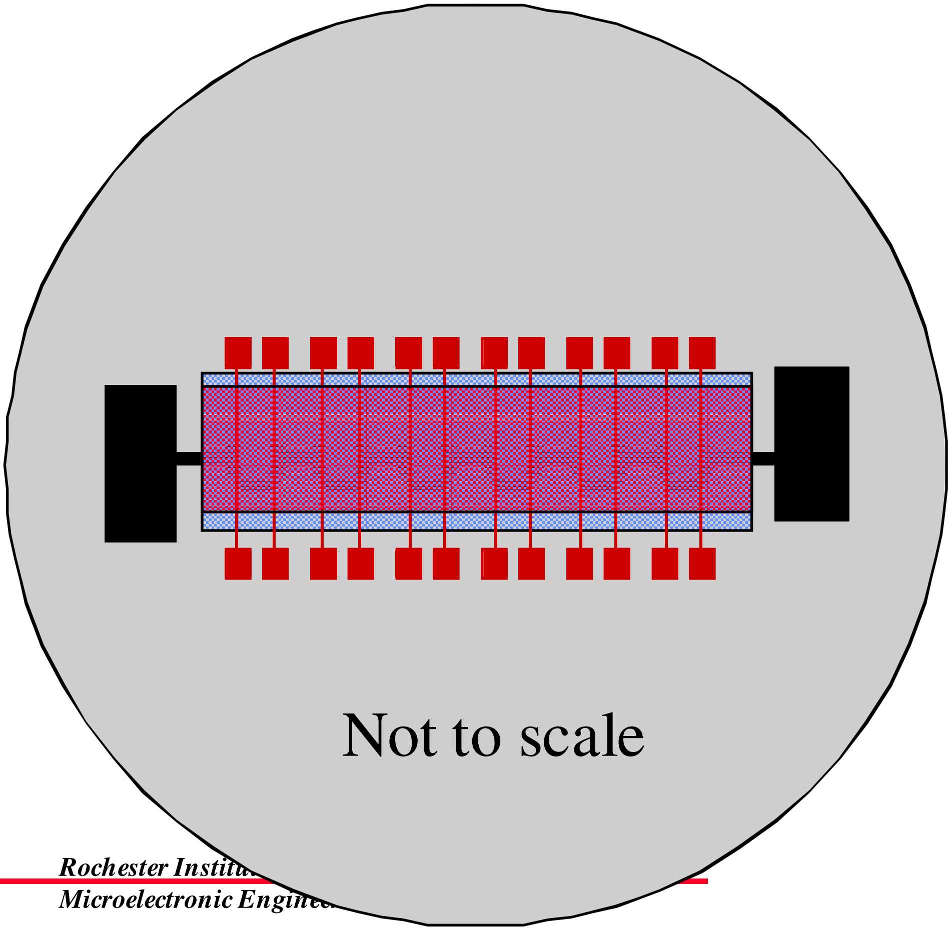
THERMAL ACTUATED PERISTALTIC PUMP

Fabrication Process

- Anisotropically etch pump pattern in silicon wafer
- Glue 80µm thick slip glass cover across channel section
- Place resistance heaters above diaphragm
- Glue patterned rubber insulator or pattern photoresist over channel section

THERMAL ACTUATED PERISTALTIC PUMP

Fabrication Process Continued



- 🟥 Heater
- 🟦 Diaphragm
- 🟥 Insulator
- ⬛ Channel

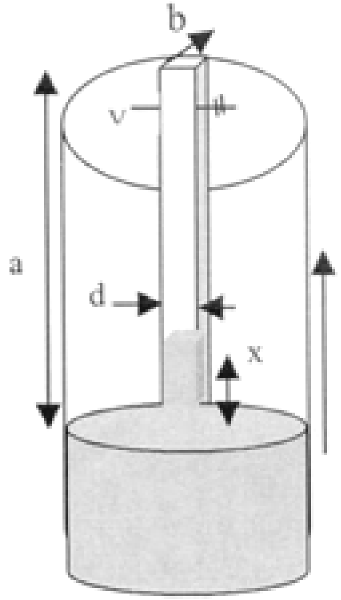
PUMPING FLUIDS WITH VOLTAGE

Santosh Kurinec, April 2, 2003

Liquid Motion by Electric Field

Force between the plates of the capacitor pulls the dielectric liquid so as to increase the capacitance.

$$C = C1 + C2 = \varepsilon \frac{bx}{d} + \varepsilon_0 \frac{b(a-x)}{d} = \frac{b}{d}[\varepsilon x + \varepsilon_0 (a-x)]$$



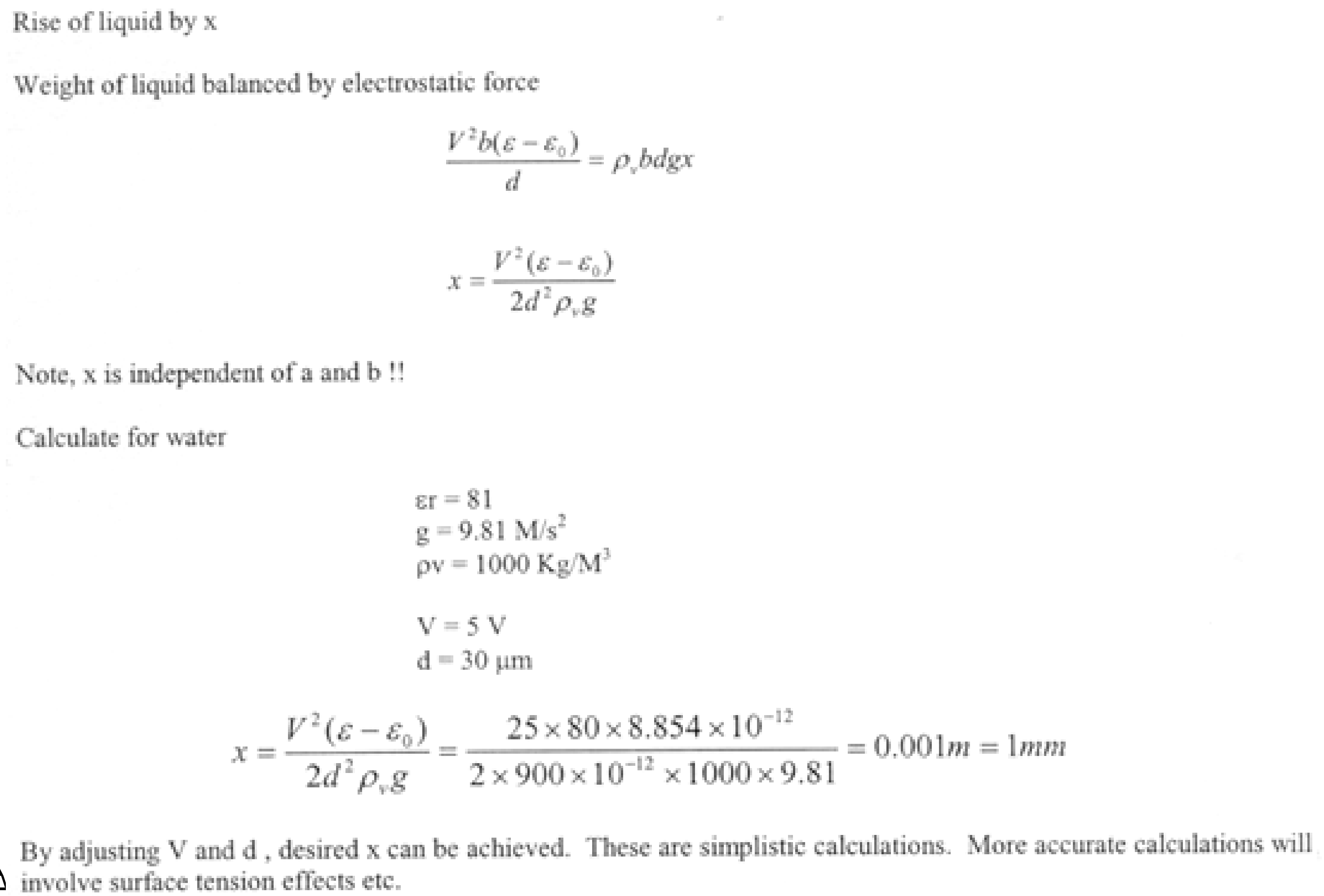
Electrostatic energy stored

$$W(x) = \frac{Q^2}{2C} = \frac{Q^2}{2(C1 + C2)} = \frac{Q^2 d}{2b[\varepsilon x + \varepsilon_0 (a-x)]}$$

Force

$$F_x = -\frac{\partial W_e}{\partial x} = \frac{Q^2 d(\varepsilon - \varepsilon_0)}{2b[\varepsilon x + \varepsilon_0 (a-x)]^2} = \frac{bQ^2(\varepsilon - \varepsilon_0)}{2dC^2} = \frac{V^2 b(\varepsilon - \varepsilon_0)}{d}$$

PUMPING FLUIDS WITH VOLTAGE



Rise of liquid by x

Weight of liquid balanced by electrostatic force

$$\frac{V^2 b(\varepsilon-\varepsilon_0)}{d} = \rho_v bdgx$$

$$x = \frac{V^2(\varepsilon-\varepsilon_0)}{2d^2\rho_v g}$$

Note, x is independent of a and b !!

Calculate for water

εr = 81
g = 9.81 M/s^2
ρv = 1000 Kg/M^3

V = 5 V
d = 30 µm

$$x = \frac{V^2(\varepsilon-\varepsilon_0)}{2d^2\rho_v g} = \frac{25\times 80\times 8.854\times 10^{-12}}{2\times 900\times 10^{-12}\times 1000\times 9.81} = 0.001m = 1mm$$

By adjusting V and d , desired x can be achieved. These are simplistic calculations. More accurate calculations will involve surface tension effects etc.

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2. IEEE Journal of Microelectromechanical Systems.

HW – APPLICATIONS VALVES AND PUMPS

1. Find another publication describing the fabrication of a MEMs valve or pump. Describe the fabrication sequence in your own words. Attach a copy of the paper.