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A micromachined silicon valve driven by a miniature bi-stable electro-magnetic actuator

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Abstract

In this paper a novel combination of a micromachined silicon valve with low dead volume and a bi-stable electromagnetic actuator produced by conventional machining is presented. The silicon valve part, $7 \times 7 \times 1$ mm^3 in dimensions, is a sandwich construction of two KOH etched silicon wafers with a layer of chemical resistant silicone rubber bonded in between. This middle layer provides the flexibility needed to move the valve boss positioned in the top wafer during valve operation, but also results in improved sealing if the valve is closed. In order to drive the valve, a dedicated bi-stable electromagnetic actuator has been designed by applying a finite element software package. The resulting actuator consists of a spring-biased armature that can move 0.2 mm up and down in a magnetically soft iron housing, incorporating a permanent magnet and a coil. This large stroke makes the valve particle tolerant. A major advantage of the bi-stable design is that only electrical energy is needed to switch the valve between the open and closed state. The actuator has been manufactured by conventional machining and was attached to the individual silicon valve parts resulting in a valve with a footprint of 7×7 mm^2 and a height of 21 mm. The valve showed an open/closed ratio of more than 100 at 0.1 bar. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Microvalve; Bi-stable; Electromagnetic actuator

1. Introduction

Microvalves are important components in various fluidic applications such as miniaturized chemical analysis systems. These systems, also known as micro Total Analysis Systems (μTAS) [1–3], can be assembled from individual components such as micropumps, microreactors and detectors. These components can be placed on a fluidic board with integrated fluidic channels to interconnect all individual parts, similar to a printed circuit board in electronics [4]. A major advantage of this miniaturization is that diffusional processes such as mixing and heating, which are required in any chemical analysis, equilibrate much faster thereby drastically decreasing assay times. Another benefit of downscaling is that the use of expensive chemical reagents can be reduced and that sample volumes in the order of only a few μl are required for an analysis. However, to fulfil these benefits the dead volume in all fluidic components should be minimized.

Minimized dead volumes can be achieved by adopting silicon micromachining techniques such as wet KOH etching. A fully integrated, batch fabricated silicon microvalve was described by Jerman [5,6]. This valve consists of two KOH etched wafers bonded together. The orifice was positioned in the lower wafer while in the upper wafer a membrane with closing boss has been machined. On top of this circular silicon diaphragm, 8 μm thick and 2 mm in diameter, a 5 μm layer of aluminum was deposited resulting in a 'bi-metallic' membrane. This membrane can be heated by sending an electric current through the metal layer. As a result of the difference in thermal expansion of aluminum and silicon, the membrane could be moved upwards thus opening the valve. The resulting valves have dimensions of only $4 \times 4 \times 0.8$ mm^3 and as a consequence can potentially be a cheap mass product. A disadvantage of this fully integrated design is that it can be used only in combination with gases and that an electrical power in the

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order of a few hundred milliwatts is continuously needed to keep the valve open. A side effect of this power consumption is heating of the valve itself as well as other system components.

A hybrid combination of a micromachined valve and a conventional piezoelectric stack actuator was described by Esashi [7]. This valve consists of a sandwich construction of two etched silicon wafers. The orifice was situated in the bottom layer while the closing boss was in the top layer. To move the boss up and down to open respectively close the valve, a commercially available piezoelectric stack was used. A major disadvantage of this type of actuator is that only very small displacements of about 10 μm can be obtained thereby limiting the open/close ratio of the valve and inducing a strong temperature dependence due to thermal expansion of the stack. Another disadvantage is the complex assembly of the construction and the fact that, similar to the previous discussed valve, energy is needed in the open position of the valve.

Besides valves described in the scientific literature, commercially on/off (micro)valves are available, however, the authors are not aware of any bi-stable actuated valves. A typical solenoid actuated on/off valve for use in chemical analysis instruments measures about 9 × 30 mm, requires over 1 W of power and has an internal volume of about 200 μl (miniature solenoid valve nr. 11600, Omnifit, Cambridge, U.K.) The smallest available solenoid valve known has a diameter of 5.6 mm and a length of 21 mm (INKA122421 VHS V-Standard port valve, The LEE, Westbrook, CT, USA). However, 500 mW of electrical power is required to keep the valve in the open position. Also the internal volume of the valve is still large (35 μl).

To reduce the power consumption as well as the internal volume, a novel combination of a micromachined silicon valve and a dedicated miniature bi-stable electromagnetic actuator has been developed. Silicon micromachining was chosen in order to minimize the dead volume of the valve whilst a conventional machined miniature actuator was applied to meet the stroke and force required. Moreover, silicon micromachining was chosen because it enables the future integration of other system components such as micro filters (drug delivery applications) and sensors within the valve. Especially sensors based on thin film technologies (i.e., conductivity cells, temperature sensors, amperometric cells, etc.) can easily be integrated in the presented design [8]. In this paper, the batch production of micromachined valve parts and the computer-assisted design of the bi-stable electromagnetic actuator will be described.

2. Valve construction

2.1. Micromachined valve part

Micromachining of silicon has been adopted as technology to manufacture the valve part in order to minimize the dead volume. Fig. 1 shows a cross-section of the silicon part of the valve in the closed and open position and a perspective view of this part. As can be seen, the valve is a sandwich construction of two micromachined wafers with a flexible silicone rubber membrane in between. This construction is familiar to the pinch valve presented in Ref. [9] but in the present design a second silicon wafer is applied to provide a closing boss. The fluid in and outlet holes are situated in the bottom layer, whilst the closing boss is in the upper layer. By moving this boss upwards the valve can be opened for gas or liquid flow. Effective closing can be obtained if the boss is firmly pressed downwards by an appropriate actuator. Sealing is enhanced by the use of flexible silicone rubber rather than silicon/silicon contact as applied in the earlier discussed microvalves and is expected to result in low leakage flow and particle tolerant operation. In the current design, the dead volume of the valve is formed by the in and outlet holes which is estimated to be about 1 μl.

2.2. Bi-stable electromagnetic actuator

To drive the micromachined valve part, a miniature actuator capable of producing a stroke of 200 μm and exerting a downward closing force has been developed. The required stroke was chosen relatively large with respect to the earlier discussed valves because of the flexible properties of the silicone rubber membrane and to provide a valve opening large enough to handle unfiltered fluids containing particles or cells such as whole blood. It was

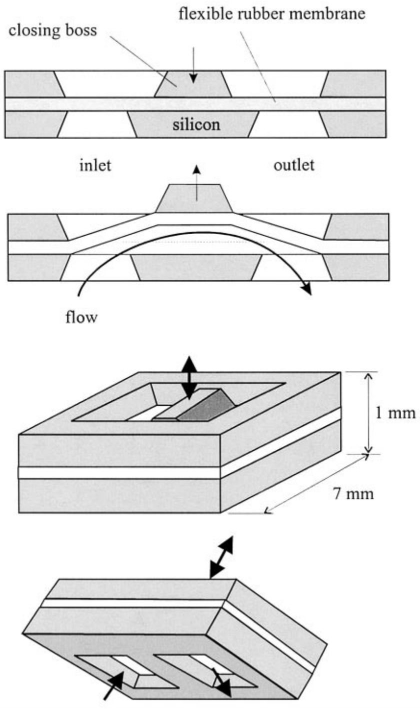

Fig. 1. Cross-section (top) and perspective view (bottom) of the micromachined valve part.

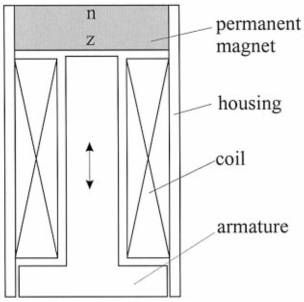

Fig. 2. Cross-section of a generalized bi-stable cylindrical electromagnetic actuator suitable for driving the valve part.

also beneficial to minimize the energy consumption of the actuator. Because these requirements could not be met by existing micromachined actuators, a miniature electromagnetic actuator produced by conventional machining has been designed.

Fig. 2 shows a generalized bi-stable electromagnetic actuator. The working principle adopted in this type of actuators is also applied in bi-stable relays and commercially available linear actuators for driving mechanical constructions such as latches for hard disk read/write heads. However, a dedicated design is required for driving the micromachined valve part.

Basically, the actuator under study consists of a spring-biased soft iron armature inside a soft iron housing incorporating a permanent magnet and a coil. In the (open) position indicated in this figure the armature is held in contact with the top of the housing by the magnet and the valve boss is retracted allowing fluid flow. By sending an electric current of appropriate direction and amplitude through the coil, magnetic flux acting against the permanent magnet is generated. If this counteracting flux reaches a certain threshold, the net holding force of the permanent magnet is reduced to such a low level that the force of the spring pushes the armature downwards to close the valve. If the actuator has switched from the open to the closed position, the electrical current can be switched off. To open the valve again, current is sent through the coil in the other direction, which will attract the armature. As soon as the armature contacts the magnet, the current can be switched off again because the magnet provides a holding force larger than the force of the spring. Because of the two stable positions of the armature, only short current pulses are required to switch the valve between the open and close position. To hold the valve in either position, no energy is needed which is highly beneficial in low power applications or in applications where heating of the valves is not allowed.

3. Actuator design

In this section the computer-aided design of the bi-stable electromagnetic actuator will be described. To model the behavior of the actuator a computer package based on the finite element method (FEM) was applied (MagNet 5.2, Infolytica, UK). This package allows the calculation of electromagnetic systems in 2.5 dimensions, i.e., linear and rotational symmetric configurations.

To result in an optimal design of the actuator, the actuator housing was given its maximum allowed diameter of 7 mm to fit it without overlap onto the micromachined valve part while the length was set to 19 mm in order to result in overall valve dimensions of D7 × 20 mm^2. Based on these dimensions, a design that finally could be manufactured with standard precision engineering and materials was made (Fig. 3).

To maximize magnetic flux and consequent forces the armature and housing were modeled in soft iron (relative magnetic permeability μ_r 5000, saturation at 1.5 T) while the magnet applied in the modeling was a commercially available disc of NeFeB magnetic material, which is known for its high flux density (coercive force H_c 8.276 10^5 A/m, pole strength B_r 1.14 T). Standard magnet dimensions where chosen because the ceramic-like material is difficult to machine. After setting up a FEM model of the design, a number of calculations were performed to investigate the resulting forces as a function of actuation current and armature position.

After defining the geometry and materials of the actuator within the software package, for the two stable positions of the armature the resulting forces were calculated for different situations. First the magnetic force on the armature in the closed position was estimated. The resulting graphs of the magnetic flux lines and flux density are plotted in Fig. 4. As can be seen from this figure no magnetic flux lines are outside the system indicating that the actuator is insensitive to external magnetic fields and that the actuator itself does not produce magnetic fields which can interfere with other system components. It can also be seen that the maximum flux density of 1.56 T is in the top of the armature near the permanent magnet. The resulting attractive force on the armature in this position is calculated to be 2.15 N.

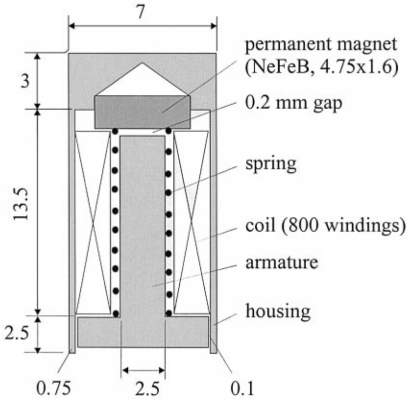

Fig. 3. Cross-section of the bi-stable electromagnetic actuator under study (dimensions in millimeters).

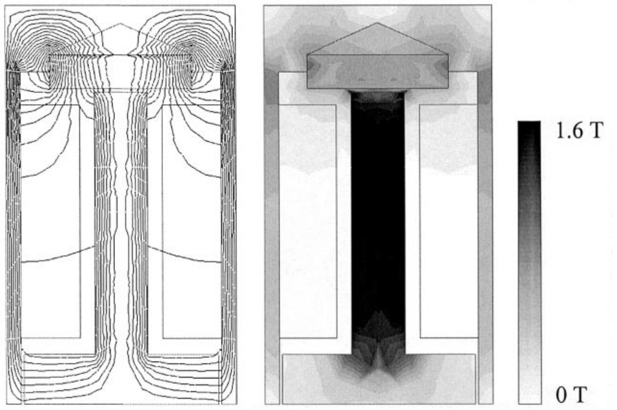

Fig. 4. Calculated magnetic flux lines (left) and corresponding flux density (right) in the closed state (armature in the lower position, zero current).

To calculate the force on the armature if a positive current is sent through the coil, different amplitudes of current expressed in Ampere turns [At], were chosen. This unit is the product of the current and the number of turns of the coil and can be seen as the electromagnetic ‘effort’ put in an electromagnetic system.

Next the holding force was calculated in the open position of the actuator when the armature contacts the magnet. Fig. 5 shows the magnetic flux lines and flux density in this position if the coil is not energized. In this case, the maximum flux density is increased to 1.9 T due to the decreased air gap. The holding force is increased to 2.7 N.

Now a negative current is sent through the coil to counteract the magnetic flux of the permanent magnet (see Fig. 6). As can be seen from this figure the point of maximum flux density is shifted downwards on the armature, thereby decreasing the flux density at the contact area of the armature and the magnet. This decreasing flux density results in a decreasing magnetic force. Fig. 7 shows the calculated forces as a function of armature position (up or down) and electric input. From this graph, a number of parameters can directly be determined. First, the holding force F_{hold} in the ‘open’ position follows from the ‘armature up’ graph at $i = 0$. The spring force F_{spring} will be given this value to maximize the net closing force:

$$F_{\mathrm{spring}} = -F_{\mathrm{hold}}. \tag{1}$$

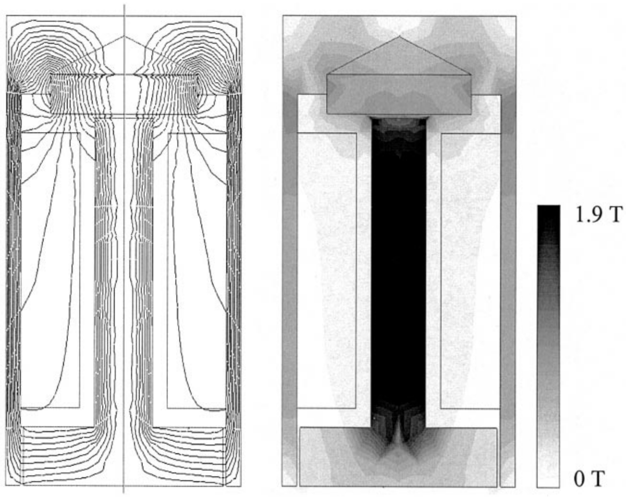

Fig. 5. Calculated magnetic flux lines (left) and corresponding flux density (right) in the open state (armature contacting the permanent magnet, zero current).

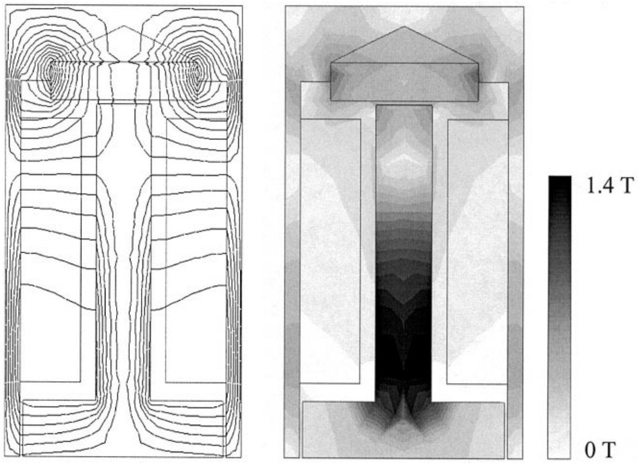

Fig. 6. Calculated magnetic flux lines (left) and corresponding flux density (right) in the open state (armature contacting the permanent magnet, −400 At electric input).

If the spring force is higher in this position, the armature will not be held in place by the holding force of the magnet. As soon as a current is applied as to oppose the magnet, the holding force diminishes and becomes smaller than the spring force, the armature is released downwards and closes the valve. To estimate the net closing force of the armature pushed down by the spring, the graph repre-

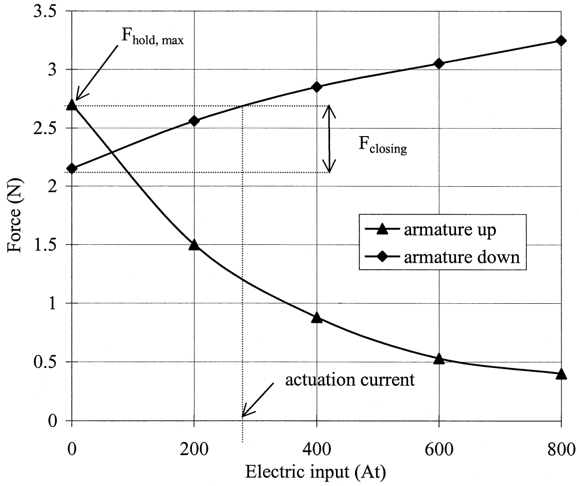

Fig. 7. Calculated forces on the armature as a function of armature position and electric input.

senting the force in the lower position should be looked up at $i = 0$ (see figure). It follows that this net closing force F_{closing} is about 0.55 N. In order to attract the armature up again, the current i should be increased up to the point where the exerted force exceeds the spring force F_{spring}. It can be seen that an electric input of about 300 At is needed.

4. Experimental

4.1. Micromachining process scheme

After cleaning a batch of 4″ ⟨100⟩ silicon wafers a 1 μm thick low stress silicon nitride layer was deposited using a standard Low Pressure Chemical Vapor Deposition process (LPCVD). This layer was patterned on both sides of the 'top' wafer incorporating the moving boss as well as on both sides of the 'bottom' wafer containing the fluid in and outlet. After this patterning, on the bottom wafer an 'anti-bonding' layer was applied to prevent adhesion of the silicone rubber membrane to the seat thereby defining the flow path. In the next step, a special pre-formed layer of silicone rubber was applied between the two wafers. The chemical bonding is promoted by a specially developed adhesive which was activated during a high temperature/pressure vulcanization step with typical cure times of about 2 min at 200°C. The last processing step was KOH wet etching of the resulting sandwich construction (see Fig. 8). The silicone rubber material was formulated to withstand the 33% KOH etching solution at 75°C for many hours. After rinsing the batch of valves, the sandwiches were sawed in individual pieces of $7 \times 7 \times 1$ mm^3 (see Fig. 9).

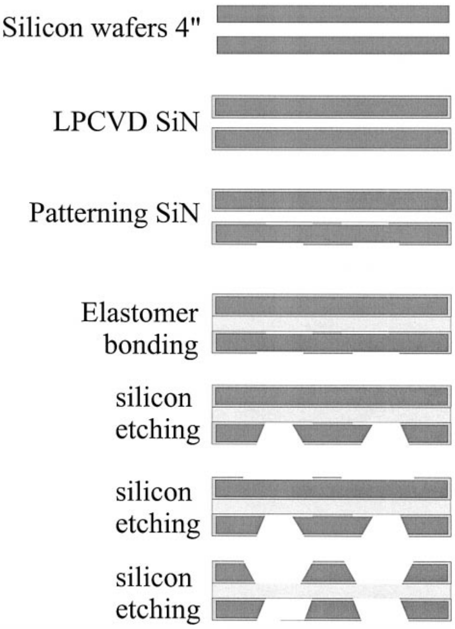

Fig. 8. Process steps for the micromachined valve part.

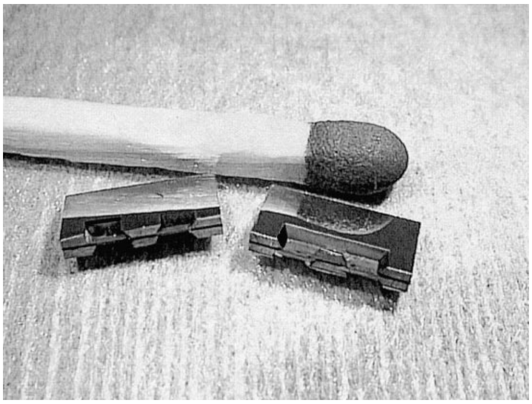

Fig. 9. Photograph of the micromachined valve part (sawed over the centerline to show the sandwich construction).

4.2. Miniature actuator

The housing and armature were produced from soft iron on a precision lathe with a tolerance of about 50 μm. The magnet was a commercial available pressed NeFeB disc 4.75 mm in diameter and 1.6 mm thick (Pörschke, Höchst, Germany). A coil having 800 windings have been made with a special winding tool using 112 μm thick copper wire having a temperature sensitive polymer coating. After winding, the coil was connected to a current source and energized to heat it up to 150°C to melt the coating. After cooling, the windings adhered and the coil could be released from the winding tool. A standard spring was chosen and adapted to the required length and strength of 2.7 N. After manufacturing of the individual parts, the actuator was carefully assembled and functionally tested for bi-stability using a current source.

4.3. Final assembly and testing

Finally, the assembled and tested actuator was attached to a micromachined valve part. First, the armature was glued to the boss using epoxy. Then, the housing was placed over the armature, positioned and fixated with epoxy. A photo of the final device is shown in Fig. 10. For testing purposes, the assembled valve was pressed on a Perspex$^{®}$ base plate containing integrated flow channels and O-rings. This base plate was connected to a computer controlled fluidic test bed, which provides filtered water at regulated pressures and accurate flows. First, the flow resistance for the open valve was determined by applying a pressure of 0.1 bar and measuring the flow of water. Also the leak flow for the closed valve was determined by

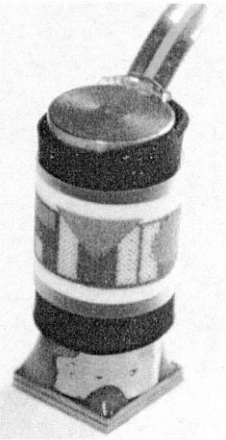

Fig. 10. Photograph of the realized device.

applying liquid pressures up to 0.5 bar and measuring the flow.

5. Results and discussion

First, the bi-stability of the actuator was tested and found to work properly. This was done by applying an alternating 500 mA 100 ms current pulses through the coil which correspond to 400 At. These pulses resulted, according to the simulations, in a magnetic force large enough to attract the armature biased by the 2.7 N spring and open the valve (see Fig. 7, 2.85 N attracting force at 400 At). After attracting the armature, a negative current pulse of 500 mA reduced, according to simulations, the holding force well under the spring force of 2.7 N resulting in closure of the valve.

To determine the flow resistance of the valve in the open position, a liquid pressure of 0.1 bar (10^4 Pa) was selected. At this pressure the flow was 11.4 μl/s which gives a hydraulic resistance of 8.8×10^{11} [Pa s m^{-3}].

Next the leak flow for a closed valve was determined by varying the liquid pressure between 0 and 0.5 bar (0–5 10^4 Pa) and measuring the flow. The results are plotted in Fig. 11. It can be seen from this figure that the leakage increases exponentially with the applied pressure indicating that the flow resistance decreases with increasing pressure. The reason for this behavior is probably the upward bending of the flexible silicone rubber sheet around the boss (see Fig. 12). If the pressure is increased, the two indicated leakage flow paths increase in cross-section and as a consequence, their flow resistance decrease.

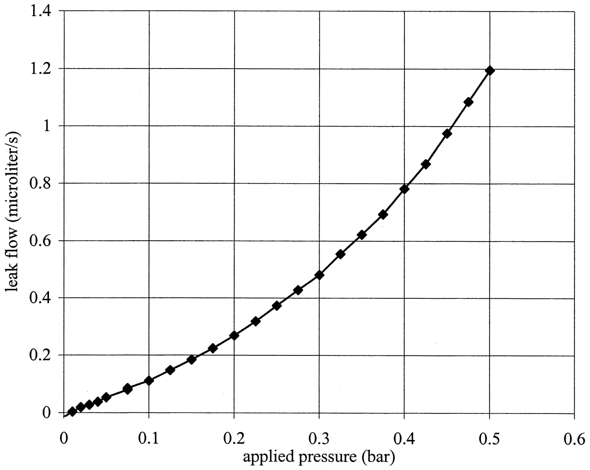

Fig. 11. Leakage of the closed valve for increasing liquid pressures.

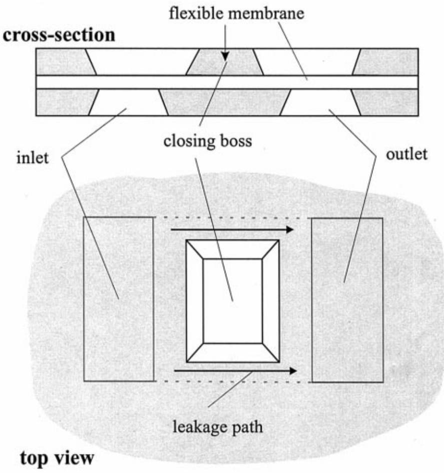

Fig. 12. Possible leakage pathways for liquid through the closed valve. These paths increase in cross-section at increasing pressures due to the flexible nature of the membrane.

6. Conclusions

A novel combination of a micromachined valve and a conventional machined miniature actuator has been prototyped. A special developed process was applied to bond a chemical resistant silicone rubber membrane between two 4″ silicon wafers. By applying micromachining the dead volume of the valve could be minimized to about 1 μl. To drive the valve a bi-stable electromagnetic actuator was designed with the aid of a finite element computer package. This actuator, which was produced using conventional machining, showed bi-stable behavior as predicted by simulations. This bi-stability reduced the energy consumption because only electrical power is needed to switch the valve between the open and closed position. To hold the valve in the open or closed position no current is needed. The relative large valve opening of 0.2 mm suggests that the valve can be used in combination with unfiltered fluids such as whole blood.

A general advantage of combining micromachined structures with conventional systems is that the high precision of micromachining processes is only applied where this accuracy is required. This approach can result in silicon devices small enough to allow cheap mass-production. Moreover, the use of silicon micromachining processes enables the integration of other micro system components within the valve, thus providing a higher level of integration, which can be beneficial in particular applications. Although in this paper silicon was applied, but other materials such as stainless steel and plastics can also be adopted because methods are available to machine these materials with the required precision. However, micromachining of silicon has a higher potential to further downscale the valve.

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Sebastian Böhm has a background in applied physics and is a PhD student at the MESA Research Institute of the University of Twente since 1996. His project aims at the integration of the microdialysis sampling technique with micro Total Analysis Systems (μTAS). In 1997 he started the company miniTEC in which he offers consultancy in micro system technology.

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Gert-Jan Burger studied electrotechnical engineering at the University of Twente and received his MSc degree in 1991. After this he worked at the MESA Research Institute on the development of a MEMS slider motion monitoring system for measuring contact and friction forces in rigid disk storage devices. For this work he received his PhD in 1995. Since then, he has been working as Technical manager in the field of MEMS design and fabrication at Twente MicroProducts.

Fred Roseboom received his Bachelor degree in Chemical Engineering in 1986. He has a 10-year experience in product- and process development in the precision rubber molding industry at Vernay Europa. One of his specialisations is the technology of bonding rubbers to metals and plastics.