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Pneumatic MEMS In-Channel Microvalves with In-Plane Control Ports for Micro Fluidic Systems Integrated on a Chip Surface

Hidekuni Takao[1,2,*] and Makoto Ishida[1,2]

[1]Intelligent Sensing System Research Center, Toyohashi University of Technology,
1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan
[2]JST-CREST, Japan Science and Technology Agency,
4-1-8 Honcho, Kawaguchi-shi, Saitama 332-0012, Japan

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In this paper, the concept, examples, and applications of pneumatic MEMS microvalves with in-channel structure and in-plane pneumatic control port for pneumatic actuation are introduced and discussed in detail. The important feature of this microvalve design is the combination of ‘in-channel’ inlet and outlet and ‘in-plane’ pneumatic transmission port for pneumatic actuation, which enables the microvalve to be positioned in various microfluidic systems on a chip surface. Pressure connections from the pressure chamber in horizontal direction are formed in the microvalve, which makes it possible to connect all the ports and the pressure control device with other fluidic channels or electronic circuits integrated on the same chip surface. Also, the separation between the pressure chamber and the drive microheater can be achieved in thermopneumatic microvalves using this pressure transmission path. This feature is effective to separate high-temperature regions from the channel region and becomes a great advantage for some kinds of micro-total-analysis-system (micro-TAS) devices with heat-sensitive samples.

In the article, the concept and features of this microvalve design are discussed first. Then, example microvalve devices with pneumatic and thermopneumatic actuators with an in-plane pressure control port based on the concept are introduced. Finally, novel applications in microfluidic systems with microvalve features integrated on the chip surface are discussed. Microvalves with high connectivity to fluidic channels and electronic devices on the same plane are a basic and important component in such applications.

*Corresponding author, e-mail address: takao@eee.tut.ac.jp

1. Introduction

Because of the remarkable advance of recent MEMS technology and the demand for microvalves in the biotechnology field, microvalves realized by MEMS technology have been developed in the field at a stretch. One application of microvalve devices is as a fluidic control device, and another is as an energy transducer. A major application of microvalves is in "micro total analysis systems" (micro-TAS). MEMS microvalves are one of the essential elements in micro-TAS to handle and control liquid samples in micro channels. Many kinds of microvalves using various actuator mechanisms have been reported. Piezoelectric,[1–3] electromagnetic,[4,5] and electrostatic[6–9] actuators are generally used in MEMS microvalves considering their advantages. Also, microvalves for pneumatic applications with bimetallically actuated diaphragms have been reported.[10,11] Pneumatically[12,13] and thermopneumatically[14–16] actuated microvalves have relatively simple drive mechanisms using fluidic power transmission principle, and a large actuation force can be obtained easily. The simplicity of microvalve structure is important to improve the yield of devices when a number of microvalves are integrated to form large-scale microfluidic systems. In addition, "in-channel" structure of microvalve[17] is important to connect many fluid channels and microvalves easily with minimum dead volume. Thus, an in-channel type microvalve with an pneumatic actuator is basically suitable and promising to fabricate large-scale integrated fluidic systems with high fabrication yield.

A pneumatic microvalve is a kind of microvalve whose flow channel gap between the movable part and the valve seat is driven and controlled by a compressed air pressure. There are two major types of pneumatic microvalves. One is the 'pure' pneumatic microvalve which is driven by compressed air pressure directly. Another is the thermopneumatic microvalve in which the drive pressure is created by thermal expansion of a fluid controlled by the electric power of heaters. Figure 1 shows cross-sectional

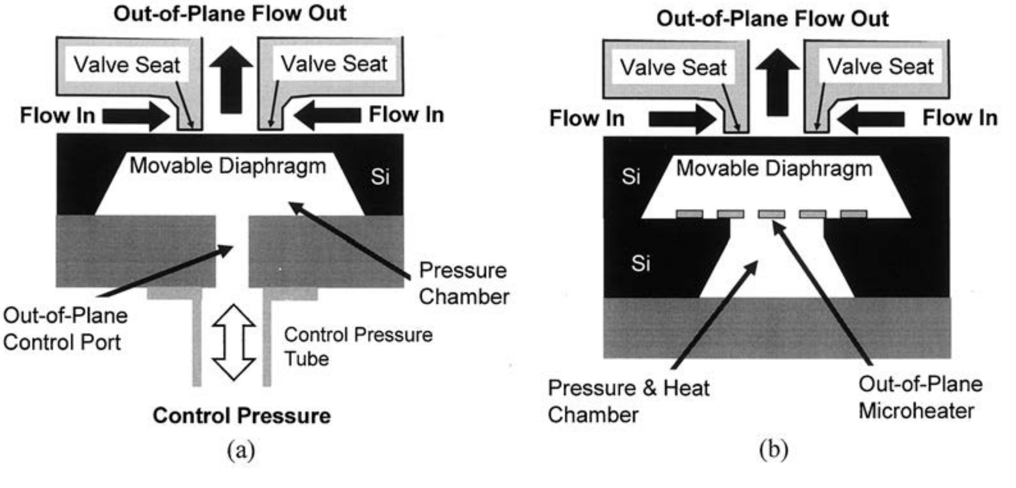


Fig. 1. Cross sections of representative pneumatic microvalves; (a) a typical pneumatic microvalve structure, (b) a typical thermopneumatic microvalve structure.

structures of representative pneumatic microvalves with MEMS technology. In the typical structure of a pure pneumatic microvalve shown in Fig. 1(a), the control port at which the control pressure of the valve conductance is applied is put on the reverse side of the flow channel beyond the diaphragm. Thus, the control pressure tube is connected to the reverse side of the microvalve device.

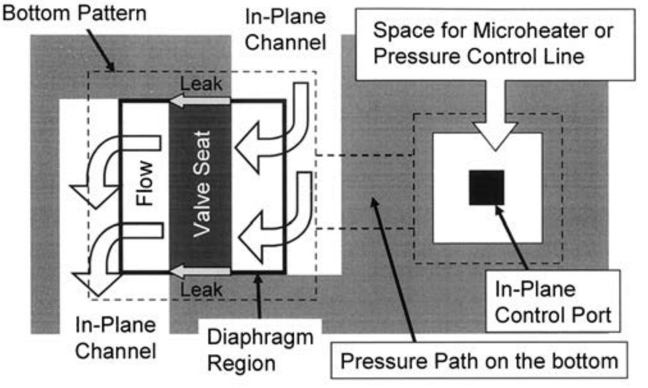
In a typical thermopneumatic microvalve structure shown in Fig. 1(b), the heater for creating a compressive fluid pressure is set inside the pressure chamber, and the electronic power is provided to the heater below the diaphragm. Thus, the heater and the flow channels are formed on different planes (wafer surfaces). These two structures have inlet and outlet ports on the opposite side of the diaphragm to the pressure control port or the drive microheater. This situation is not so suitable for the integration of a microfluidic system on a chip surface, since the connectivity of all the terminals and ports with other channels or electron devices is more difficult. If pneumatic microvalves have the pressure control port or the drive microheater on the same side of the flow channel, many components and devices in a microfluidic system can be integrated on the same plane like electronic integrated circuit (IC), and ease of fabrication, integration density, and connectivity of each microvalve are improved.

Focusing on the flow channel structure, many microvalves have ‘out-of-plane’ flow direction which is perpendicular to the movable diaphragm like the examples shown in Fig. 1. Although such microvalves facilitate various microvalve designs with high sealing ability, it is difficult to connect microvalves to each other on a chip surface for integration of microfluidic systems. An “in-channel” microvalve structure is thus suitable to convert many fluid channels into microfluidic channels with high connectivity.

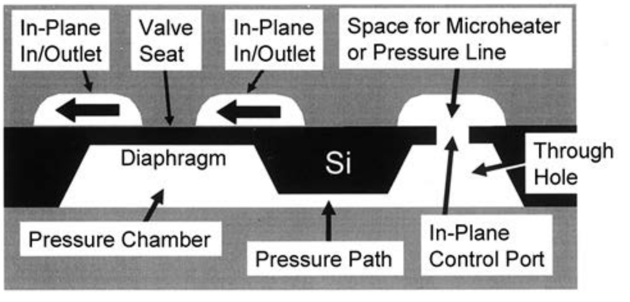
In this paper, a pneumatic “in-channel” microvalve structure with an ‘in-plane’ control port which is suitable for integration in microfluidic systems on a chip surface is reconsidered and discussed. The important feature of this microvalve design is the combination of an ‘in-channel’ inlet/outlet and an ‘in-plane’ pneumatic control port for pneumatic actuation, which enables the microvalve to be positioned in various microfluidic systems on a chip surface. In the article, concept and features of this microvalve design for integrated microfluidic systems on a chip surface are introduced first, and example devices and applications of pneumatic and thermopneumatic microvalves based on the concept are totally discussed.

2. Features of the Microvalves with In-Plane Control Ports

Figures 2(a) and 2(b) show the basic structure of the MEMS pneumatic microvalve with a pressure transmission path extended from the pressure chamber to form the ‘in-plane’ control port discussed in this paper. The major features of the microvalve are the pressure transmission path connected to the side of the pressure chamber, and the ‘in-channel’ inlet and outlet ports. The movable part of the microvalve for fluid flow control is a thin diaphragm, and the valve seat faces the diaphragm surface. The flow channel of the microvalve from inlet to outlet is a gap between the valve seat and the diaphragm, and it is formed by a pressure difference between the microvalve inlet port and a pneumatic drive pressure applied to the pressure chamber. If the pressure of the pressure chamber is not low enough relative to the inlet port, the channel gap does not achieve enough width to



(a)



(b)

Fig. 2. Basic structure of the MEMS pneumatic microvalve with horizontal pressure extension structure discussed in this paper; (a) top view of the microvalve with horizontal pressure transmission path, (b) cross section of the microvalve with pressure transmission path and vertical through-hole connecting the bottom path to the surface of the chip.

allow flowing of the sample fluid from inlet to outlet. If the pressure of the pressure chamber is low enough relative to the inlet port pressure, a channel gap is formed according to the amplitude of pressure difference. Figure 2(a) shows the top view and cross section of the pneumatic microvalve. Since the inlet and the outlet of the microvalve are placed on the same side of the diaphragm, they can be fashioned into a microfluidic channel as shown in Fig. 2(a). Also, the horizontal pressure extension path formed on the bottom of wafer enables the microvalve to be connected with other fluidic devices or electronic devices integrated on the chip surface.[18] Making the vertical through-hole connecting the bottom path to the surface of the chip as shown in Fig. 2(b), the pressure chamber can be connected to a heater (actuator) chamber or a microfluidic channel formed on the surface side. This feature enables the microvalve to integrate all the essential components (i.e., inlet, outlet, and pneumatic drive power source) on the surface side. As a result, the pneumatic microvalve can be controlled by a control pressure provided from a surface microfluidic channel directly or from a microheater integrated in the surface chamber. This feature is advantageous to connect the microvalve with other microfluidic devices on the same surface since the structure of microvalve has a full in-channel structure. Also, the pressure chamber can be separated from the drive microheater in thermopneumatic microvalves using the pressure transmission path. In the following section, examples of pneumatic and thermopneumatic microvalves based on the concept of an 'in-plane' control port are introduced and discussed.

3. Example Microvalves

3.1 *MOSFET-like pneumatic silicon in-channel microvalve with in-plane control port*

As the first example, a pneumatic in-channel microvalve with an in-plane control port is introduced.[19,20] Figure 3 shows the schematic diagram of the microvalve cut at the middle of the structure. This microvalve has a pure pneumatic drive mechanism, and all the ports of the microvalve (inlet, outlet, and control ports) and the surface fluid channels are formed in the same plane. In the top glass, through holes to access the microfluidic network on the silicon surface are formed. In addition, the upper half of the surface fluid channels and barriers (which works as valve seats) are formed by shallow etching of the glass. Pneumatically actuated movable diaphragms and the lower half of fluid channels are formed on the surface of the silicon substrate. Pressure transmission paths for pneumatic actuation of the diaphragm are formed between the wafer backside and the bottom glass. The pressure chamber and a surface fluid channel are connected by the pressure transmission path and the wafer through hole. The in-plane control port formed on the surface side realizes high connectivity to the pneumatic line. Also, a fluid channel (pneumatic line) can control plural microvalves connected on the surface. Therefore, this pneumatic microvalve is effective in reducing the dead volume and is suitable for integration in microfluidic networks using a batch fabrication process. A novel and interesting feature of this microvalve is its similarity in characteristics with MOS field-effect transistor (MOSFET),

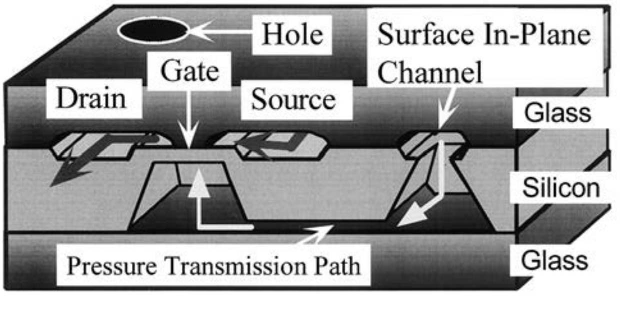


Fig. 3. Schematic diagram of the pneumatic microvalve with MOSFET-like characteristics cut at the middle of the structure. This microvalve has a pure pneumatic drive mechanism, and all the ports of the microvalve (inlet, outlet, and control port) and surface fluid channels are formed in one plane.

which is the elemental device in recent semiconductor ULSIs. This 'MOSFET-like' microvalve can work as a transistor-like device in a fluid channel network, because its operation behavior in a fluidic circuit is analogous with the MOSFET. In the analogous relationship between the microvalve and MOSFET, 'pressure' and 'flow-rate' of air in fluidic circuits correspond to 'voltage' and 'current' in electronic circuits, respectively. 'Flow-rate' (current) of channel is controlled by 'pressure' (voltage) of gate in pneumatic microvalves (MOSFET). On the basis of the analogy, 'inlet', 'outlet', and 'control' ports are indicated as 'source', 'drain', and 'gate' in Fig. 3. A close-up photograph around the gate region of the fabricated MOSFET-like microvalve is shown in Fig. 4. The circle pattern is the through hole formed in the top glass. The ports of the MOSFET-like microvalve (seen as source and drain) can be connected to optional surface channels by merely changing the layout patterns of the channel boundary.

Measured flow characteristics of the fabricated MOSFET-like microvalve are shown in Fig. 5. Figure 5(a) shows the relationship between "drain flow-rate" Q_D and 'gate pressure' P_{GS}. The 'drain to source pressure', P_{DS} was kept at a constant pressure of –500 hPa in this measurement. This characteristic corresponds to the I_D-V_{GS} characteristics of MOSFET, and shows the 'transconductance' of the microvalve. It is clearly shown in the figure that there is a 'threshold gate pressure' of the flow around –500 hPa similar with V_{TH} of MOSFET. The threshold pressure corresponds to the critical gate pressure where Q_D starts flowing through the channel, and it is important for the device performance. Recently, a quantitative flow model of microvalve including the threshold pressure has been reported in ref. 21. Figure 5(b) shows the measured relationship between Q_D and P_{DS} with P_{GS} kept at –540, –700, and –820 hPa. This corresponds to the I_D-V_{DS} characteristics of MOSFET. In the case where P_{DS} is relatively small, Q_D increases linearly with P_{DS} like the "linear region" of MOSFET. If P_{DS} increases in magnitude, Q_D is gradually saturated due to the increased fluid friction near drain region. This saturated drain flow behavior results in nonlinear curves like the "saturation characteristic" of MOSFET.

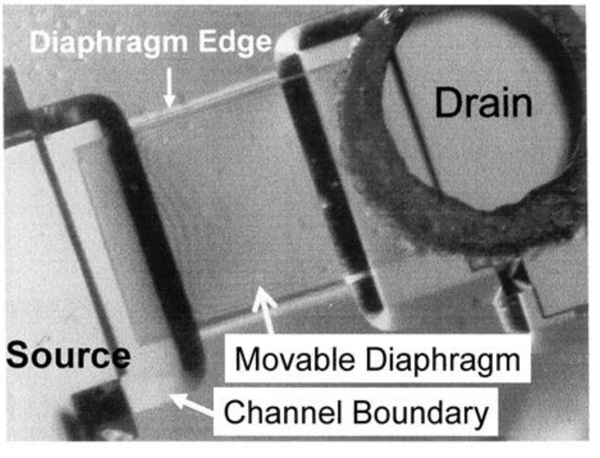


Fig. 4. A close-up photograph around the gate region of the fabricated MOSFET-like microvalve.

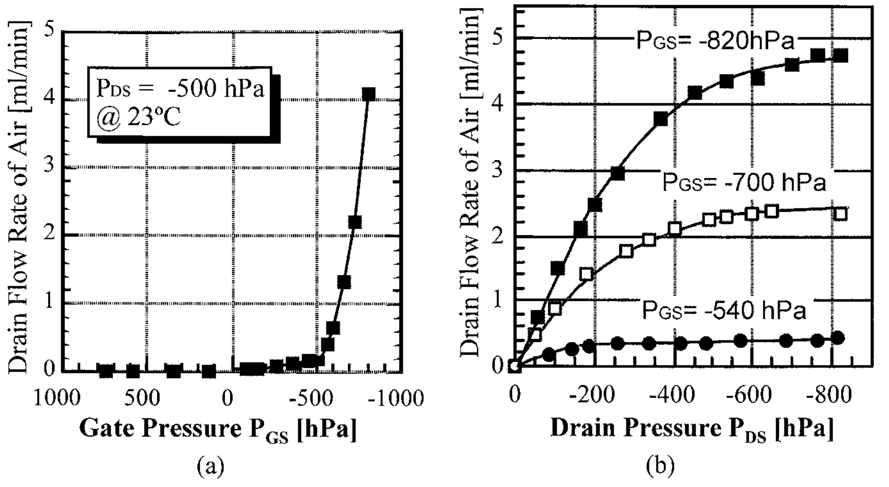


Fig. 5. Measured flow characteristics of the fabricated MOSFET-like microvalve: (a) relationship between drain flow-rate Q_D and gate pressure P_{GS}. The drain pressure P_{DS} was kept at a constant pressure of –500 hPa in this measurement, (b) relationship between Q_D and drain pressure P_{DS} in the cases that P_{GS} was kept at –540, –700, and –820 hPa, respectively.

Utilizing the analogous relationship between the MOSFET-like microvalves and MOSFETs, various functional fluidic circuits similar to MOSFET circuits can be realized. An example application of the microvalve is discussed in § 4.1.

3.2 *Thermopneumatic in-channel microvalve with PDMS diaphragm*

The second example of an in-channel microvalve with an in-plane control port is a thermopneumatic microvalve.[22,23] Figure 6 shows a schematic of the thermopneumatic microvalve with separated control chamber configuration based on the concept of this paper. This microvalve is configured by the top glass, the middle micromachined silicon layer with movable diaphragm, and the bottom glass. Figure 7 shows a cross section of the thermopneumatic microvalve. Fluid flow is controlled by the channel gap between the top-glass (valve seat) and the movable diaphragm similar to the previous example. The movable diaphragm of this microvalve is made by polydimethylsiloxane (PDMS). Since PDMS has much lower Young's module than silicon, a large channel gap can be formed by a small pressure difference. The diaphragm is actuated by a pneumatic pressure controlled by a Au-microheater integrated on the front side of the wafer. The bottom pressure transmission path connects the pressure chamber and the heating chamber where the microheater controls the temperature and pressure of air. Since the microheater is formed on the same surface with the diaphragm, it is easily connected to the integrated electronics on the silicon wafer for microvalve control. Also, the inlet and the outlet of the microvalve with an in-channel structure can be configured in a surface microfluidic channel network. Operation of the microvalve is very simple. Under the initial condition, the channel gap

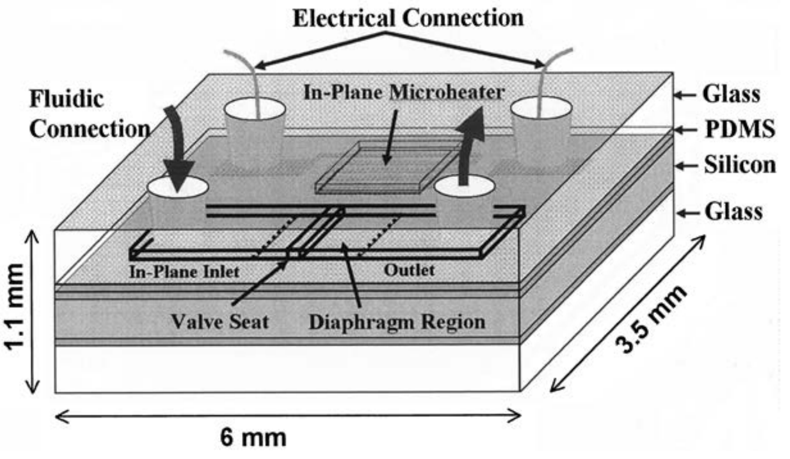


Fig. 6. Schematic of the thermopneumatic microvalve with separated chamber configuration based on the concept of this paper. Microheater intagrated on the same plane with microfluidic channel is connected with the pressure chamber through the bottom pressure transmission path.

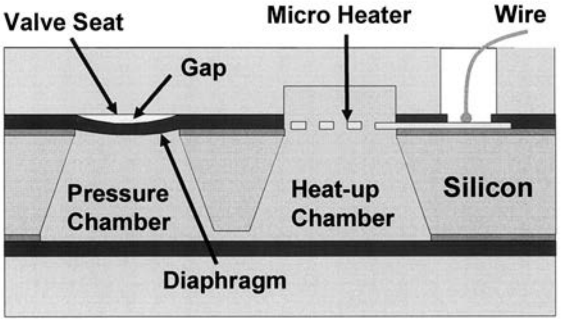


Fig. 7. Cross section of the thermopneumatic microvalve with the separated chamber configuration.

between the top glass and the diaphragm is closed since the surface of the PDMS diaphragm and the valve seat are formed to be on the same plane in the fabrication process.[23] The channel gap is opened when the inlet pressure becomes higher than the actuator chamber pressure allowing flow from the inlet to the outlet through the channel gap. If an electrical power is applied to the microheater, pressure of the heater chamber increases, and the increased pressure is transmitted to the actuator chamber through the pressure transmission path. As a result, the pressure of the actuator chamber also increases to close the gap between the diaphragm and the valve seat. If the applied electrical power is high enough, the gap is closed, and the fluid sample is cut off. In this configuration, the liquid sample which is flowing on the PDMS diaphragm can be kept away from direct thermal contact with the microheater, thanks to the in-plane heater. Photographs of the fabricated components of the thermopneumatic microvalve are shown in Fig. 8. Figure 8(a) shows the top glass part including etched microfluidic channels, area for microheater chamber space, and access holes. The lower two holes are formed for electronic access to the bonding pads of the microheater. In Fig. 8(b), a Au-microheater is formed as a floating bridge structure across the heater chamber for thermal-isolation. The dynamic response of the microvalve switching operation with a DI-water sample is shown in Fig. 9. Although the microvalve has a long response time (around 10 s to switch the flow), a very low leak rate (below the detectable lower limit of the measurement system) is obtained for the water sample. It is considered that a small unevenness/gap existing on the valve seat is enveloped

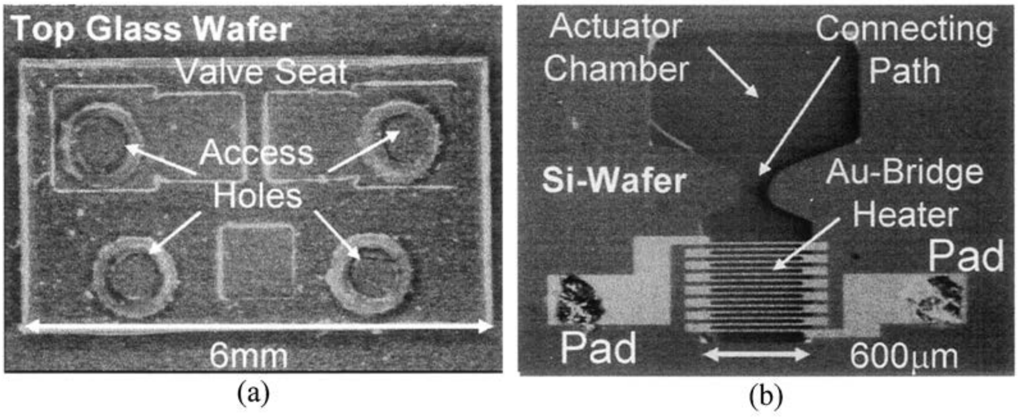


Fig. 8. Photographs of the fabricated components of the thermopneumatic microvalve; (a) top glass part including etched microfluidic channels, area for microheater chamber space, and access holes, (b) Au-microheater formed in floating bridge structure across the heater chamber for thermal-isolation. The actuator chamber is connected to the heater chamber by the pressure transmission path.

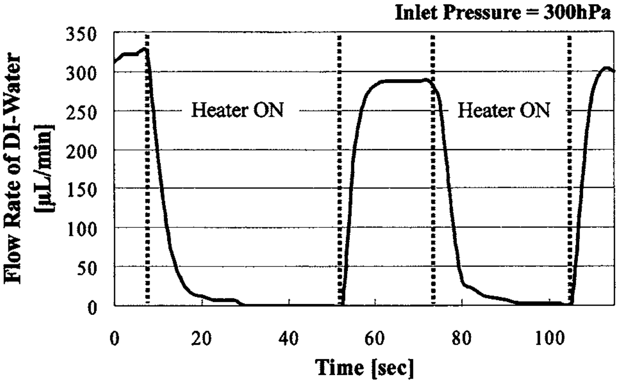


Fig. 9. Dynamic response of the microvalve switching operation for DI-water sample.

by the softness of the PDMS diaphragm. In our experiments, it was difficult to determine the leakage level of the microvalve for both liquid and gas samples. However, behaviors of liquid and gas samples in actual microvalves are complicated, and theoretical considerations are important for detailed evaluation.[24]

In the next section, example applications of the microvalves in this section are introduced and discussed with practical research results.

4. Applications of Microvalves with In-Plane Control Ports

4.1 *Microfluidic integrated circuits with similarity with MOS integrated circuits*

Utilizing the MOSFET-like flow characteristic of the pneumatic microvalve discussed in § 3.1, novel fluidic processing circuits with functions similar to MOSFET circuits can be constructed on a chip surface.[19,25] As is well known, there is an analogous relationship between electrical (or electronic) circuits and fluidic circuits. 'Pressure' and 'flow-rate' in fluidic circuits correspond to 'voltage' and 'current' in electronic circuits, respectively. Since the shapes of the *Q*-*P* (flow-rate and pressure) characteristics of microvalve shown in Figs. 5(a) and 5(b) are very similar to the typical shapes of the *I*-*V* (current and voltage) characteristics of a MOSFET, it is considered that fluidic circuits with 'analogous' shape of transfer functions from input to output can be realized with 'analogous' MOS circuit topology by replacing voltage and current with pressure and flow-rate, respectively. Similar functions realized by MOS circuit technology, such as signal (or energy) amplification, band filtering, and oscillation can be realized in pressure and fluid flow by the novel circuit technology.

Since the microvalve has the feature that all the ports of the microvalve (inlet, outlet, and control port) and surface fluid channels are formed in one plane, integrated 'fluidic' circuits on a microchip can be realized. Figure 10 shows the common source amplifier with two of the microvalves for amplification of 'pressure.' Figure 10(a) shows the circuit topology, and Fig. 10(b) shows a chip photograph of the fabricated pressure amplifier. This amplifier has a reference level of pressure at 0 hPa gauge pressure (i.e., atmosphere pressure). The microvalve turns on at negative gauge gate pressures over the threshold pressure, and the operation is compared to that of p-MOSFETs. Thus, the operation of the common source amplifier may also be compared to that of a p-MOS inverting amplifier. Figure 11 shows the DC transfer characteristic of the pressure amplifier. In this measurement, +720 and –830 hPa are used as positive and negative power supply from 0 hPa, respectively. If both microvalves are turned on and are in the saturation region where Q_D almost becomes a constant of P_{DS} change, the output pressure change of the amplifier becomes much larger than the input pressure change. This transfer function is used as an analog pressure amplifier with inverse polarity gain. If the entire range of the DC transfer characteristic is used, this circuit works as the NOT gate of digital circuit.

Since the shape of the *Q*-*P* characteristics of the microvalve has a similar shape with MOSFET, a simulation model of MOSFET using the SPICE circuit simulator can be applicable to model microvalve flow characteristics. This modeling makes it possible to calculate the transfer function or simulate DC transfer curves of integrated fluidic circuits

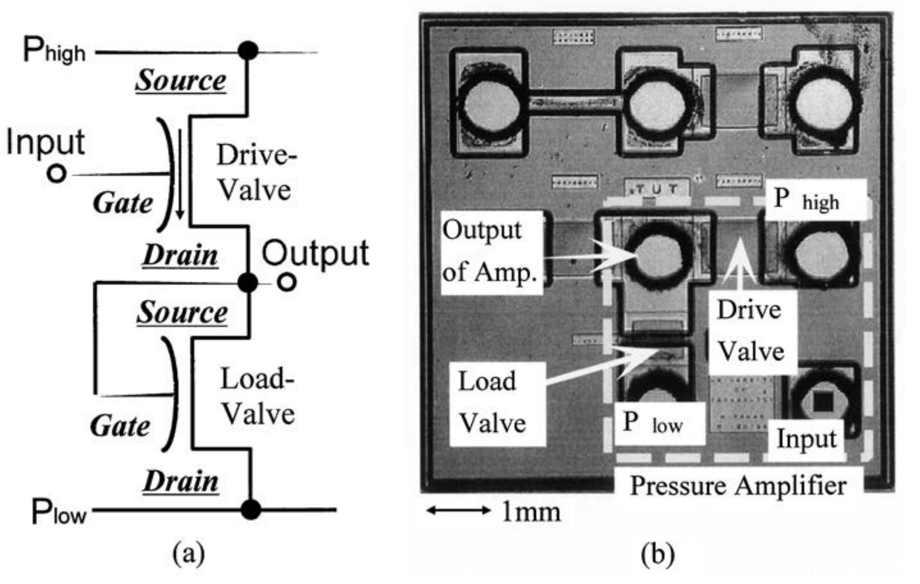


Fig. 10. Common source amplifier with two of the microvalves for amplification of ‘pressure,’ (a) the circuit topology, (b) a photograph of the fabricated amplifier including two microvalves.

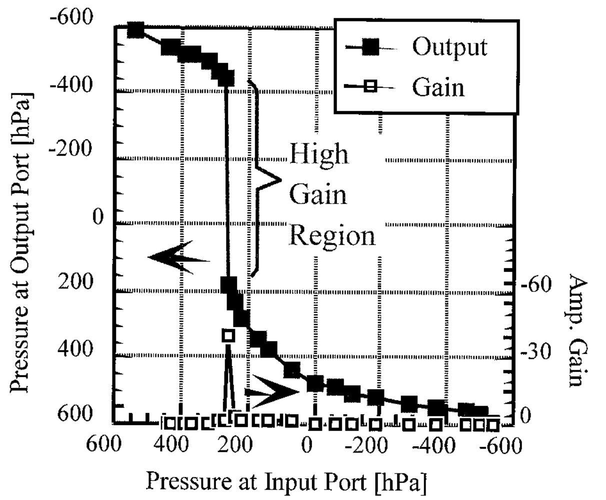


Fig. 11. DC pressure transfer characteristic of the pressure amplifier. In this measurement, +720 and –830 hPa are used as positive and negative power supply from 0 hPa, respectively.

composed of MOSFET-like microvalves. Figure 12 shows a fitting result of a SPICE model using the measured *Q-V* characteristics of the microvalve shown in Fig. 5(b). The level 2 model of MOSFET is used, and voltage 1 V and current 1 mA are considered as pressure 100 hPa and flow-rate 1 ml/min, respectively in the fitted model. Although the shapes of curves are not perfectly fitted, important device parameters for performance analysis of circuits such as 'trans-conductance' and 'drain conductance' are well fitted. Thus, basic characteristics of microfluidic circuits such as amplification gain and logic threshold are simulated with SPICE program with a good accuracy.

Recently, a concept of micropneumatic logic with complementary pneumatic microvalves has been introduced by Henning.(21) The concept of micropneumatic logic is based on the analogy with CMOS logic in microelectronics, while the concept of microfluidic integrated circuit in this study is based on the single-channel MOS technology. Considering the essential merits of CMOS technology, the concept reported in ref. 21 is promising for the technology of microfluidic integrated circuit.

4.2 *Integrated micro fluidic analysis systems on a chip surface*

Since the microvalves based on the concept in this paper have high degree of connectivity with fluidic channel networks on a chip surface, they are also applicable to microanalysis systems integrated on a chip surface. Actually, the thermopneumatic microvalve introduced in § 3.2 was developed for an integrated micro-blood-testing-system. Figure 13 shows a conceptual diagram of a micro-TAS for blood testing proposed by our group and HORIBA Ltd., Japan in ref. 22. It includes integrated circuits for system control and signal

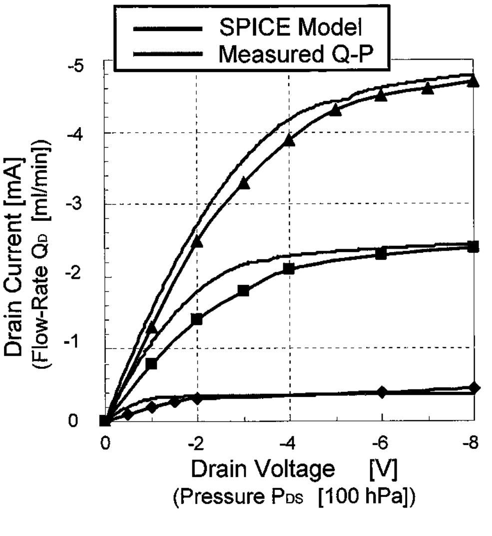


Fig. 12. A fitting result of MOSFET model for SPICE to the measured *Q-V* characteristics of the microvalve shown in Fig. 6(b). Voltage 1 V and current 1 mA are considered as pressure 100 hPa and flow-rate 1 sccm, respectively in the fitted model.

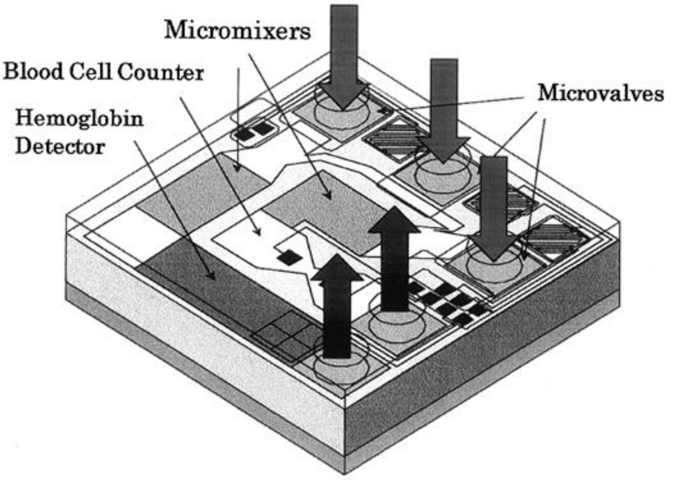


Fig. 13. A conceptual diagram of a micro-TAS for blood testing proposed by our group and HORIBA Ltd., Japan. It includes integrated circuits for system control, integrated sensors for blood test, fluidic processing device such as mixer, and plural microvalves for sample handling.

processing, integrated sensors for blood test, fluidic processing devices such as mixers, and plural microvalves for sample handling. All the functional components are integrated on the chip surface, and the microvalves are incorporated into a surface fluidic channel network which connects the sample preparation devices and sensors for liquid sample analysis. Our concept is based on the belief that using silicon-IC technology and MEMS technology, highly integrated multifunctional systems will be realized in a small total die size.

Sensors for integrated blood test systems have been developed. Absorption photometric detectors with a multireflection structure(26) and two 45°-mirrors(27,28) have been realized with integrated electronic detectors and circuits. Also, a blood cell counter for counting of red and white blood cells per unit volume sample of blood has been developed.(29) Their sensor components are put in surface flow channels on silicon as sensing elements in the blood test systems. As the thermopneumatic microvalves(23) are controlled by microheaters integrated on a chip surface, a liquid sample which is flowing through the thermopneumatic microvalve can be kept away from direct thermal contact with the microheater. This feature is effective in preventing coagulation of protein in blood samples and becomes a great advantage for micro-TAS devices with protein samples.

Batch fabrication of functional components on the surface side of the chip guarantees high accuracy positioning of each component since no bonding step is necessary to connect each component. This feature makes it possible to minimize tolerances and spaces between the integrated components, and is effective for achievement of highly integrated systems realized in a small total die size. Microvalves with a high degree of connectivity to surface fluidic channels and electronic devices are a basic and important component in such integrated microfluidic systems on a chip surface.

5. Conclusions

In this paper, the concept, examples, and applications of pneumatic MEMS microvalves with an in-channel structure and an in-plane pneumatic transmission port for pneumatic actuation have been introduced and discussed. The important feature of this microvalve design is the combination of an ‘in-channel’ inlet/outlet and an ‘in-plane’ pneumatic transmission port for pneumatic actuation, which enables the microvalve to be incorporated with various microfluidic systems on a chip surface. A pressure extension path from the pressure chamber in the horizontal direction is formed in the microvalve, which makes it possible to connect all the ports and pressure control devices with other fluidic channels or electronic circuits integrated on the same chip surface.

Applications of the microvalves based on the concept, to novel microfluidic systems integrated on chip surfaces, have been introduced. The full in-channel pneumatic microvalve with MOSFET-like characteristics can be used to form functional fluidic circuits, such as pressure amplifiers, on a chip surface. The thermopneumatic microvalve with separated heater chamber makes it possible to separate high temperature regions from the microvalve channel region. The feature becomes a great advantage for micro-TAS devices manipulating heat-sensitive samples. The design concept of a microvalve with a high degree of connectivity to surface fluidic channels and electronic devices will be promising and effective in the design and fabrication of highly integrated microfluidic systems fabricated on a silicon chip surface.

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About the Authors

Hidekuni Takao was born in Kagawa, Japan, in 1970. He received his B.E. and M.E. degrees in electrical and electronic engineering in 1993, 1995, respectively, and his Ph.D. degree in electronic and information engineering in 1998, all from Toyohashi University of Technology, Aichi, Japan. He was a Post Doctoral Research Fellow with the Japan Society of Promotion of Science (JSPS) from 1998 to 1999. He joined the faculty of Department of Electrical and Electronic Engineering in Toyohashi University of Technology from 1999 as a Research Associate. Since 2005, he has been an Associate Professor with Intelligent Sensing System Research Center (ISSRC) in Toyohashi University of Technology. He is currently working on microfluidic devices for micro-total-analysis-systems (micro-TAS), CMOS-MEMS smart sensors, and high resolution smart tactile imaging device realized by MEMS technology.

Makoto Ishida was born in Hyogo, Japan, in 1950. He received his Ph.D. degree in electrical engineering from Kyoto University, Kyoto, Japan, in 1979. Since 1979, he has been at Toyohashi University of Technology, Aichi, Japan, where he is now a Professor of the Department of Electrical and Electronic Engineering. He is working on smart microchip devices, such as epitaxial micro-Si probe arrays, heteroepitaxial growth, and processes of SOI material, including epitaxial Al2O3 insulator and Si films, and their device applications, including sensors and ICs in the Electron Device Research Center in Toyohashi University of Technology. He is the leader of the 21th Century COE program “Intelligent Human Sensing” sponsored by the Ministry of Education, Culture, Sports, Science and Technology, and head of the Intelligent Sensing System Research Center in Toyohashi University of Technology.