2002

A comparative study on actuation methods in microvalve design

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San Jose State University

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**A COMPARATIVE STUDY ON ACTUATION METHODS
IN MICROVALVE DESIGN**

A Thesis

Presented to

**The Faculty of the Department of Mechanical and Aerospace Engineering
San Jose State University**

In Partial fulfillment

of the Requirements for the Degree

Master of Science

by

Yen-Chang Hu

August 2002

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APPROVED FOR THE DEPARTMENT OF MECHANICAL
AND AEROSPACE ENGINEERING

Dr. Tai-Ran Hsu

Dr. Ji C. Wang

Dr. Li-Wei Lin, University of California at Berkeley

APPROVED FOR THE UNIVERSITY

ABSTRACT

A COMPARATIVE STUDY ON ACTUATION METHODS IN MICROVALVE DESIGN

by Yen-Chang Hu

A comparative study on three actuation methods used in a microvalve design is investigated. The microvalve body has an overall dimension of $0.05 \times 2 \times 2 \text{ mm}^3$. It operates in the atmospheric pressure and at room temperature with a 2 mL/min flow rate for the gas. The valve body is attached to three different actuation chambers using thermal, electrostatic forces, and piezoelectric actuation. A plausible fabrication process for the valve with different actuation methods is also presented. Design merits, such as the weight, the overall size, the energy consumption, and the fabrication cost for each of these actuation methods are analyzed and reported.

Piezoelectric actuation appears the best of these three actuation methods for the designed microvalve. It not only has moderate power consumption during the operation of the designed valve, but it also requires the realistic voltage. Moreover, the fabrication process for piezoelectric actuation is not as complicated as that for the electrostatic actuation, and the overall size and weight for piezoelectric actuated valve is acceptable among these methods. The optimal actuation method for this designed valve is thus by piezoelectric actuation.

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1.0 Introduction

Microflow devices are used to control or sense fluid flows in the order of micro liter per minute ($\mu\text{L}/\text{min}$). Micromachining technology has been used to fabricate gas flow sensors in the early stage of this development. Microvalves and micropumps are among the most promising devices of micromachining products. Microflow devices fabricated by micromachining technology have very small dead volume, which enables precise control of minute flow with fast response time. Microflow sensors also can be integrated into micro devices in order to obtain feedback control. In such applications, these devices will replace the traditional parts used in the conventional systems. This thesis will evaluate several key design parameters that are related to microvalves. These parameters will provide further reduction in dead volume and for better performance.

1.1 Objective

The objective of this thesis research is to evaluate the relative merits of normally closed microvalves for gas flow using three selected actuation methods. Through this study, the optimal actuation method of microvalves will emerge.

1.2 Microvalves Applications

Microfluidics is one of the major application areas in micro electro mechanical systems (MEMS). Microvalves are essential components in microfluidic systems. Unlike conventional valves for pressure and flow control with magnetic actuation driven by

solenoids, microvalves are developed with miniaturization that integrates IC technique. Due to its small size, microvalves offer many unique advantages over conventional valves, such as low power consumption, low manufacture cost, and fast response.

Due to its excellent performance, the application of the microvalves is involved in diverse fields. First, microvalves are preferred to be used in the biomedical systems. A drug delivery device that follows a certain programmed schedule to transport small amounts of drug to the required locations instead of multiple injections a day as done in the traditional way is possible with the use of microvalves. (Reynaerts, 1996) We may also implant microvalves to artificial organs such as an artificial heart to provide more precise and reliable performance. Other applications of microvalves include fertility control, flow cytometry, and DNA sequencing with remote control in biomedicine. (Enderling, 2001)

Another large market in nonmedical applications is in industrial pneumatic systems, where such small microvalves are needed in many traditional applications. Another major area of application is in the automobile industry, where numerous servo-motors can be replaced by a pneumatic system with many microvalves. There are still other applications, such as inkjet printer head, fluid injection analysis, chemical processing and analysis, atmospheric and temperature control equipment (Reynaerts, 1996), environmental monitoring, and cooling of integrated circuit chips.

Moreover, a recent publication was reviewed and evaluated by (Mueller, 2000) from the perspective of microspacecraft application.

1.3 Motivation for the Current Research

The widespread application of microvalves as presented in a class on “Introduction to MEMS (Micro-Electro-Mechanical Systems) Design and Packaging” a year ago at SJSU motivated my interest in an in-depth study of this particular micro devices. I have learned several kinds of actuation methods, for instance, thermal actuation, electrostatic actuation, piezoelectric actuation, and SMA (shape memory alloy) actuation, etc. from that class. Unfortunately, no research document has showed the relative merits of these actuation methods. I was also curious about which actuation method can save more power while allows the valve to work efficiently.

Optimal actuation of microvalves has become critically important with the advent of the artificial heart. It is desirable for us to compare selected popular actuation methods and thereby to identify the most optimal actuation technique. Consequently, the focus of this thesis is to search for an optimal actuation method of microvalve design.

1.4 Scope of Research Study

For all those applications of microvalves as mentioned before, the flow rates are typically low ranging from a few micro liters down to a few hundreds nano liters per minute. The Reynolds numbers are also very low in those applications. The size of the channels in which fluid flows varies from a few micrometers to a few hundred micrometers. Gases are the commonly used medium in micro fluidics. Thus, in this paper, gases are selected as the fluids in designed microvalve. (Hsu, 2002)

Microvalves are among the most promising devices of MEMS products. Two categories have been developed in microvalves applications: active microvalves that needs actuators, and passive microvalves that lacks actuators. (Shoji, et al., 1994) Active microvalves with actuators also have two groups, which are normally opened microvalves and normally closed microvalves. (Henning, 1997) In this thesis, a normally closed microvalve with three selected actuation methods is designed and evaluated.

Until now, various actuation methods have been designed and researched for microvalves, such as solenoid plunger, piezoelectric material, shape memory alloy and bias spring, electrostatic force, thermopneumatic method, electromagnetic method, and bimetallic method. (Shoji, et al., 1994) Three of the most popular actuation methods are selected for the designed microvalve in this thesis. There are thermal actuation methods with bimetallic materials, electrostatic actuation method, and piezoelectric actuation method.

A number of parameters will be evaluated for the merits of each actuation method through a common base microvalve configuration. These parameters include power consumption, weight, overall size, the complexity of fabrication process, and the estimated cost for manufacturing and packaging.

In this thesis, Section 1 presents a brief bibliographic review and a justification for this particular study. Section 2 presents the literature study which includes the comparisons of different actuation methods in microvalves and the relevant background in the selected actuations. The configuration, geometry and dimensions of the designed microvalve, sealing solutions, the finite element analysis results, and the CAD as parts of

the IntelliSuite package (IntelliSense Corporation, 2001) are presented and discussed in Section 3. Mechanical engineering design analysis of the three applied actuation methods and computations of pressure drop and power consumption are presented in Section 4. Section 5 describes proposed fabrication processes for these microvalves. Comparison based on several important features of microvalves is presented in Section 6. The conclusion of this research study is presented in Section 7.

2.0 Literature Review

A microvalve is a key component in a microfluidic system. The actuation part is the key component in microvalves. Up to now, for the actuating mechanism of microvalves, bimetallic (Jerman, 1994, Barth, 1995), electrostatic (Ohnstein et al., 1990, Bosch et al, 1992, and Goll et al, 1997), piezoelectric (Nakagawa et al., 1990, Yeatman, 1995) and other principles have been used for this purpose. Advantages and shortcomings of these methods for special applications have been analysed and reported by (Shoji, et al., 1994). Table 1 presents a typical performance comparison of the selected actuation methods.

Table 1 Performance Comparison of Micropumps

Actuation Type	Maximum flow rate ($\mu\text{L} / \text{min}$)	Operation voltage (V)	Power consumption (mW)
Thermopneumatic	34	6	2000
Bimetallic	43	16	-
Electrostatic	850	200	1
Piezoelectric	1300	160	-
	40	100	-
Electromagnetic	20	3	900
SMA	50	-	630

Source: Yun, K., Cho, I., Bu, J., Kim, G., Jeon, Y., Kim, C., and Yoon E. "A Micropump Driven by Continuous Electrowetting Actuation for Low Voltage and Low Power Operations", IEEE, 2001, p.490

Although it is desirable to have low operation voltage and power consumption for medical devices, sizes and flow rates are equally important factors to be considered in the design. A performance comparison table of this kind as shown in Table 1 is difficult for

design engineers to appreciate which method of actuation is better than others because each of the cases cited was produced with different design specifications in configuration, dimensions, flow rates, etc.

The same ambiguity appears in Table 2, which compares four thermal valves using sealed fluid capsule expansion, aluminum/silicon bimetal, shape memory alloy, and nickel/silicon bimetal as the actuation methods. The parameters which are of interest to design engineers in evaluating microvalve performance in power consumption, actuation speed, force, stroke, cost, and package size are not readily available in published papers. One more point that needs to be mentioned is the data in Table 1 and Table 2 were mostly obtained by the experimental measurements.

Table 2 Comparison of the Four Thermal Valve Technologies

Parameter	SCE (Sealed fluid Capsule Expansion)	Al/Si Bimetal	SMA (Shape Metal Alloy)	Ni/Si Bimetal
Pressure (psid)	100	25	80	150
Flow (sccm, air or N ₂) @T=25°C	2000	100	6000	1000
Power (W)	2.0	0.5	0.29	1.03
Response time (ms)	400	100	100	200
R _{thermal} (K/W)	52	300	840	90

Source: Barth, P. W., "Silicon Microvalves for Gas Flow Control", The 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors IX. Stockholm, Sweden, June 1995, pp.25-29

Moreover, the shape of several chambers of the involved microvalves is either square or rectangle in geometry. (Esashi, et al. 1986, Bosch, et al., 1992, and Goll, et al.,

1997) These physical shapes result in more dead volume as well as heavier in weight. It may also take more time for fabrication. Valves in these geometry do not provide smooth flow. Also, the sealing problem for microvalves is still critical. (Henning, 1997) The leakage of microvalves is almost always due to poor packaging of the microvalves. (Ohnstein et al., 1990) Much improvement in this respect is required in order to reduce the leak rate.

3.0 Design Methodologies

The following approach was taken in determining the optimal actuation method for the microvalve design.

1. Conducted a thorough survey on current literature, from which a microvalve with common specifications for comparative design studies was established.

The key features of this valve include the following:

- (a) The configuration of the chamber of designed microvalve. As mentioned in the previous chapter, unlike the usual shape of microvalves in rectangle, hexagon, or octagon (Jerman, 1994), the shape of the chamber of the present microvalve is circular.
  - (b) The dimensions of the stationary body of the microvalve. The proposed dimension of the stationary part of the valve is common for all cases with different actuation mechanisms, since we want to compare the performance by these actuation methods to drive the same microvalve.
  - (c) The common flow rate. The comparison of power consumption is based on the same flow rate in valves using different actuation methods. It is desirable to know which of the three actuation methods consumes the least of energy at this specific flow rate.
  - (d) The sealing problem. A specific feature of this microvalve will be used for solving for the sealing problem.
2. Since the fluid in the present microvalve is a gas, it can be air, or gases. The proper fluidic properties are required to ensure laminar flow. For example, the Reynolds number is kept below 100 to ensure laminar flow. Unlike laminar flow, turbulent flow does not

follow the streamlines and result in large drag forces when the fluid flows over a solid surface. (Hsu, 2002)

3. Designed the actuation chambers that accommodate the three actuation methods. Close form solution methods were performed first to check if the design features are feasible by using these three specific actuation methods. This exercise provides the estimated values with range that are useful in the conceptual design stage.
4. Simulated the three actuation models by a CAD software called IntelliSuite for detailed design of these valves. Often multi layers adhered or diffused together in some components of these micro devices are involved in the modeling. Precise analysis of these complex systems is beyond the capability of conventional methods. Finite element method is used effectively as a reliable approximation. (Hsu, 2002) This software, IntelliSuite (IntelliSense 2001), specifically designed for MEMS analysis, provides material database and suggested fabrication process flows. It also incorporates the finite element method to provide appropriate solutions.
5. Compared the data obtained from the IntelliSuite CAD package with those computed by close form solutions. Estimated the pressure drop of the designed microvalve and calculated the power consumption in each actuation method. Additionally, proposed the appropriate fabrication processes for microvalve common body and the three actuation chambers.
6. Evaluated the relative merits (power consumption, weight, overall size, fabrication processes, etc.) of these valves using different actuation methods.

4.0 Microvalve Design

The valve is a normally closed type to allow gas flow at room temperature. The valve base is made of two 25 μm thick silicon layers. The actuation chamber is also made of silicon with the geometry and dimensions varying according to the adopted actuation mechanisms. The flow chamber, which is a part of the valve base, is of circular geometry. The valve has a flow rate of 2 mL/min at a pressure of 1 bar at an operating temperature of 25°C. A v-type shape with an angle of 54.74° on silicon oriented in the <100> direction is made by an anisotropic etch

Figure 4.1. The Configuration and Geometry of the Designed Valve

The bold line in the sketch represents the tip of the closing boss in the diaphragm that is 1~2 μm below the stationary openings when the valve is fully closed to ensure that these two parts have a good surface contact for effective sealing. The configuration and geometry of the cross section of the designed valve is shown in Figure 4.1.

4.1 Mechanical Engineering Design Analyses

The following is a set of conditions that were used in the mechanical engineering design analyses in this thesis.

1. For mechanical analysis, the silicon diaphragm is treated as a 3- μm thick plate, and the boss part is ignored for simplicity in computations. However, this assumption is not included in computer simulation for more precise results.
2. The required maximum deflection at the center of the diaphragm is 6 μm upward to allow for the specified gas flow rate.
3. The maximum flow velocity at various parts in the valve chamber is computed to ensure laminar flow. The maximum Reynolds number in the flow chamber was found to be 30 which makes flows in the laminar flow regime. The detail computation for this justification is presented in Appendix A.
4. The required diaphragm deflection is computed by expression derived for thin circular plates with a uniform thickness of 3 μm . Figure 4.2 presents a circular plate subjected to uniform pressure loading. (Hsu, 2002)
5. The total force required to produce such deflection for a silicon diaphragm from Equation (4-1) is $W=8.6 \times 10^{-4} \text{ N}$.

6. Due to the laminar flow pattern and the low velocity change in this microvalve chamber, the forces produced by inlet flow to the silicon diaphragm are negligible.

Figure 4.2 A Circular Plate Subjected to Uniform Pressure Loading

$$w_{\max} = \frac{3W(m^2 - 1)a^2}{16\pi Em^2 h^3} \quad (4-1)$$

where $w_{\max}$ = the maximum deflection at the center = $6 \mu\text{m}$,
 $m = 1/\nu$, ν = Poisson's ratio = 0.25 for silicon
 W = total load = $(\pi a^2)p$
 h = thickness of the silicon diaphragm = $3 \mu\text{m}$
 a = radius of the diaphragm = $800 \mu\text{m}$
 E = Young's modulus of silicon = 190 GPa

4.1.1 Thermal Actuation by Electric Resistance Heating

Thermomechanical microactuators are related to the change of the shape or the volume of a solid when it is heated or cooled from a reference state. The best-known actuators of this type are the bimaterial actuators. These strips are made from binding two materials with different coefficients of thermal expansion (CTE). Due to incompatible CTE of these materials, the strip or plate will bend when it is heated or cooled from its initial reference temperature. The same principle can be applied to produce a certain force to actuate the designed valve. (Hsu, 2002)

In the present case, a thin aluminum film $1 \mu\text{m}$ thick is attached to the silicon diaphragm as shown in Figure 4.3. The significant difference of the CTE of the two

materials causes the diaphragm to deform upward when the compound disk is heated by the passing electricity in the aluminum film. To get a better performance as well as heat and electrical isolations of the thermal effect, one thin layer of silicon dioxide film is deposited between silicon diaphragm and aluminum film. The coefficient of thermal conductivity of silicon dioxide is very low at $0.014 \text{ W/cm}^\circ\text{C}$, so this silicon dioxide layer will provide good thermal insulation, which minimizes the loss of the heat produced by the heating of the aluminum film.

Figure 4.3 The Setting for Thermal Actuation

Analysis using the IntelliSuite CAD package indicates that a 5°C temperature rise in the top surface of aluminum film can result in the required deflection of $6.43 \mu\text{m}$ at the center of the diaphragm. After trying different radius of aluminum plate for the heat supply, the radius of $325 \mu\text{m}$ of the aluminum film is determined to provide sufficient heat for the required actuation force. The radius of silicon dioxide film is the same as the aluminum film. Figure 4.4 shows the variation of the deflection of the silicon diaphragm as obtained from the finite element analysis using the IntelliSuite package. The corresponding temperature distribution is shown in Figure 4.5, which shows silicon dioxide film to be a good thermal insulator.

**Figure 4.4 The Result of the Deflection of Silicon Diaphragm by Thermal Actuation
From the Top View of the Valve Body**

**Figure 4.5 The Temperature Distributions in Copper Film and Upper Part by Thermal
Actuation in IntelliSuite**

4.1.2 Electrostatic Actuation

Electrostatic forces are used as the driving forces for many actuators. Accurate assessment of electrostatic forces is an essential part of the design of many micro motors and actuators. Two possible arrangements of electrostatic force generators were considered. They are:

(A) Electrostatic actuation by aligned electrodes

Figure 4.6 represents two charged plate electrodes separated by a dielectric material (i.e., an electrically insulating material) with a small gap, d . Air is a common dielectric medium in many applications. The electrodes become electrically charged when a voltage is applied to these plates. The capacitance, C , induced by the applied voltage can be shown as follows: (Hsu, 2002)

$$C = \epsilon_r \epsilon_o \frac{A}{d} \quad (\text{pF}) \quad (4-2)$$

in which A = the area of the plate electrode (m^2)

ϵ_r = relative permittivity of the dielectric medium

ϵ_o = permittivity of free space (vacuum) $= (1/36\pi) \times 10^{-9} \text{ pF/m} = 8.85 \text{ pF/m}$

d = the gap between the parallel plates (m)

Figure 4.6 Electric Potential in Two Parallel Plates

The charged electrodes create an electric potential as illustrated in Figure 4.6. The associated potential energy, U can be expressed as

$$U = -\frac{1}{2}CV^2 = -\frac{\epsilon_r\epsilon_oAV^2}{2d} \quad (4-3)$$

in which V =the applied voltage

The electrostatic force produced by the potential energy in the normal d -direction can be derived from Equation (4-3) to be

$$F_d = -\frac{\partial U}{\partial d} = -\frac{1}{2} \frac{\epsilon_r\epsilon_oAV^2}{d^2} \quad (4-4)$$

(B) Electrostatic actuation by overlapped electrodes

Electrostatic forces also exist along both the length and width directions of the overlapped electrodes, i.e., the top and bottom plate electrodes in Figure 4.6 are not aligned. Expressions for determining these forces are available in open literatures such as in (Hsu, 2002).

Two attempts were made in the design of the present valve using electrostatic forces as the source for actuation. These attempts are described below.

4.1.2.1 Electrostatic Actuation by Aligned Electrodes

In this first attempt, thin film disks made of copper are used as the electrodes for the generation of the required electrostatic forces for the actuation. The reasons for selecting copper for this actuation are its low electrical resistivity and high thermal conductivity.

Figure 4.7 illustrates the approximate setting for the electrostatic actuation.

Figure 4.7 The Setting for Electrostatic Actuation

The required lifting force in this case is shown in Section 4.1 and can be expressed by Equation (4-4), or

$$W = \frac{1}{2} \frac{\epsilon_r \epsilon_o A V^2}{d^2} \quad (4-5)$$

where W = lifting load (N) and the area, $A=\pi r^2$, r is the radius of the electrode films(m).

The required voltages for generating sufficient electrostatic forces with different radii of electrode plates to deflect the diaphragm were calculated using Equation (4-5).

Results are summarized below:

Table 3 The Relationship between the Radius of the Electrodes and Applied Voltage

Radius (μm)	500	550	600	650
Voltage (V)	126	114	97	90

IntelliSuite CAD package was also used to analyze this method of actuation. Two copper plates with radius of 650 μm applied with 90 volts are used to provide sufficient capacitance for the required actuation force. After analyses, the required force provided by 97V generates the deflection of 5.89 μm at the center of the diaphragm. The reason for

Figure 4.8 The Distribution of the Deflection at the Center of the Silicon Diaphragm with Different Applied Voltages

Figure 4.9 The Result of the Deflection of the Silicon Diaphragm by Charging Parallel Plates

the difference between the close form solution and that by the finite element analysis is that the force obtained from the former method is from Equation (4-1) which applies to the thin diaphragm only, but the forces generated by two parallel plates in the practical situation are required to lift both the diaphragm and the boss part. Figure 4.8 shows a

distribution on the deflection at the center of the silicon diaphragm with different applied voltages. The variation of the deflection of the silicon diaphragm obtained from the analysis using IntelliSuite package is shown in Figure 4.9.

As can be seen from the Table 3 with the analytical results, the required voltage supply is much too high to be practical. A significantly different arrangement was sought as described below.

4.1.2.2 Electrostatic Actuation by Annular Comb Drive

This arrangement is a derivative of capacitors in “parallel” surfaces, or the overlapped electrodes. An alternative arrangement with cylindrical capacitors is used as shown in Figure 4.10.

The capacitance in this case can be determined by the following expression:

$$C = \frac{2\pi\epsilon_o L}{\ln \frac{b}{a}} \quad (4-6)$$

in which, L , a and b are the corresponding length of both cylinders, the outside radius of the inner cylinder and the inside radius of the outer cylinder. (Hsu, 2002)

Figure 4.10 Cross Section of a Cylindrical Capacitor

Upon the application of a voltage to this actuation setting, an electric potential is produced as can be expressed by the following equation:

$$U = -\frac{1}{2}CV^2 = -\frac{\pi\epsilon_o LV^2}{\ln \frac{b}{a}} \quad (4-7)$$

The forces are induced with partial alignment of the cylinders in the axial direction of the circular valve chamber. The following equation is used to derive these forces:

$$F_i = -\frac{\partial U}{\partial x_i} \quad (4-8)$$

where the index i is the direction in which mis-alignment of the electrodes. In this case, the direction is the same as the axis of the symmetry of the cylinder. Consequently, the following Equation (4-9) is derived to estimate the produced actuation force.

$$F_L = -\frac{\partial U}{\partial x_i} = -\frac{\pi\epsilon_o V^2}{\ln \frac{b}{a}} \quad (4-9)$$

Thus, an alternative design by using concentric overlapped electrodes was considered. This actuator is located at the top of the valve body. It lifts the diaphragm upward when it is energized. The geometry of partial concentric comb drives is illustrated in Figure 4.11.

The following steps are used to calculate the required number of pairs of concentric electrodes for the equivalent electrostatic force.

From Figure 4.11, the annular gap between each electrode pair is 2 μm . The two radii for calculating the first capacitance force are $a = 1 \mu\text{m}$ and $b = 3 \mu\text{m}$, and the first

capacitance force is $F_1 = \frac{\pi\epsilon_o V^2}{\ln \frac{3 \times 10^{-6}}{1 \times 10^{-6}}}$

Fig 4.11. The Geometry of Part of the Concentric Comb Driver

The next pair of concentric capacitance force is $F_2 = \frac{\pi\epsilon_o V^2}{\ln \frac{7 \times 10^{-6}}{5 \times 10^{-6}}}$

And the third pair is $F_3 = \frac{\pi\epsilon_o V^2}{\ln \frac{11 \times 10^{-6}}{9 \times 10^{-6}}}$ and so on and so forth.

To sum up each capacitance force, the total force can be determined by $\pi\epsilon_o n^2 V^2$ Newtons.

In the above formulations, n is the total number of the concentric electrode pairs and V is the applied voltage.

Due to its complex geometry of this type of comb driver, a simplified model is assumed as Figure 4.12. The annular finger parts are removed for easily modeling this actuation part, and fixed boundary conditions are imposed on the circumference surface

of this circular plate. The annular force of each pair as computed from above expressions was applied at the nodes of each circle, which is built by IntelliSuite CAD package.

Therefore, the close form solution can be reached by using this simplified model easily, instead of annular finger parts. The force distribution that varies with the radius in this case is shown in Figure 4.13.

Figure 4.12 The Simplified Model of Electrostatic Comb Drive for Analysis in IntelliSuite Package

One may conclude that the 56 pairs of concentric electrodes in the model will correspond to the required voltage 65V because the forces, which vary with the radius, are not uniformly distributed. The outside radius of annular comb drive is $450\text{ }\mu\text{m}$. The variation of the deflection of the silicon diaphragm obtained from the analysis using IntelliSuite package is shown in Figure 4.14, and the maximum deflection at the center of the silicon diaphragm is $6.02\text{ }\mu\text{m}$. Thus, this alternative actuator design provides a lower voltage that is required to generate the required actuation force with smaller overall

radius of the valve. A shortcoming of this design, however, is an increase in the height of the valve from 10 μm to 20 μm .

Figure 4.13 Distribution on the Annular Forces with the Distance from the Center

Figure 4.14 The Result of Deflection of Silicon Diaphragm by Comb Drive

4.1.3 Piezoelectric Actuation

Piezoelectric materials can convert mechanical energy into electrical energy, and vice versa. When an electric voltage is applied to piezoelectric crystals, it causes the

crystal to deform in a certain direction that depends on the lattice of the piezoelectric crystal. This form of piezoelectric actuators are also known for their quick responses and the reproducibility of the mechanical deformation. Moreover, they are efficient in converting the electrical energy into mechanical energy. Therefore, piezoelectric actuators could generate sufficient forces that is required in MEMS.

In this research, a thin piezoelectric film is deposited on the top surface of the silicon diaphragm. A common piezoelectric crystal, lead zirconate titanate (PZT), is selected for this application due to its high piezoelectric coefficient ($d_{33} = 80 \sim 593 \times 10^{-12}$ m/V and $d_{31} = -94 \sim -274 \times 10^{-12}$ m/V) compared to other piezoelectric materials. (Avallone et al., 1996) The coefficient d_{33} applies when the electric field is along the polarization axis (direction 3) and the strain (deflection) is along the same axis. The coefficient d_{31} applies if the electric field is in the same direction as before, but the strain is in the 1-axis (orthogonal to the polarization axis). In the present case, a voltage is applied to both the top and bottom surfaces of PZT to generate the strain orthogonal to the plate surface. These numbers shown above varies with different compositions, so -210×10^{-12} m/V for the piezoelectric coefficient is chosen for estimation.

The required voltage to lift the circular piezoelectric film by $6 \mu\text{m}$ is estimated using the following expression from (Linnemann, et al, 1998)

$$w(r) = -\frac{3d_{31}V}{t^2}R_p^2\left(1 - \frac{r^2}{R_p^2}\right) \quad (4-10)$$

The maximal deflection $w_{\max}$ in the above equation is calculated at $r=0$, or

$$w(r=0) = w_{\max} = -\frac{3d_{31}V}{t^2} R_p^2 \quad (4-11)$$

where $w_{\max} = 6 \times 10^{-6} m$,

d_{31} = the piezoelectric coefficient of PZT = $-210 \times 10^{-12} m/V$

V = the voltage will be applied to the piezoelectric crystal

t = the thickness of the piezoelectric film

R_p = the radius of the silicon diaphragm $\cong 783 \times 10^{-6} m$

After applying the above parameters to Equation (4-11), the relationship between the applied voltage and the thickness of piezoelectric crystal film is established in Table 4 using the relation as shown below:

$$6 \times 10^{-6} = -\frac{-3 \times (-210 \times 10^{-12}) \times V}{t^2} (783 \times 10^{-6})^2$$

$$\frac{V}{t^2} = 1.55 \times 10^{10} \quad (4-12)$$

Table 4 The Relationship between Thickness and Voltage of Piezoelectric Film

Thickness (μm)	5	10	15	20
Voltage (V)	0.39	1.55	3.49	6.20

The above analysis offers an indication as how a piezoelectric film deforms under an applied electric field. In reality, however, the thin piezoelectric film is attached to a thin silicon diaphragm of the valve. The required actuation force is much larger for

bending the piezoelectric/silicon compound disk than that for thin piezoelectric disk alone.

Figure 4.15 The Setting in Piezoelectric Actuation

Consequently, a radius of 700 μm is assigned to actuate the piezoelectric film of 5 μm thick. The approximate setting for piezoelectric actuation is illustrated in Figure 4.15.

Table 5 Comparison between Hand Calculation and IntelliSuite FEM

	Required voltage	Deflection
Close form solution calculation for single piezoelectric disk	0.39V	6 μm
IntelliSuite FEM for the compound disk	4.4V	6.14 μm

A finite element analysis in the IntelliSuite CAD package was used for the electromechanical stress/strain analysis. As the setting in IntelliSuite package as in Figure 4.16, the voltage was applied to the top and bottom surface of the piezoelectric film shown in yellow color with fixed boundary conditions. This piezoelectric film is bonded to the circumference surfaces of the plate in green color. Figure 4.17 shows the variation of the deflection of the silicon diaphragm, and a comparison between close form solution

and IntelliSuite FEM is presented in Table 5. The difference of required voltage between the close form solution and finite element analysis is due to the different boundary conditions. Only a single piezoelectric disk is used in the close form solution. It is a different story when the piezoelectric disk is bonded to the silicon diaphragm, which deforms with the piezoelectric disk together. For example, the rubber bar can be bent easily by our hands. However, after the same rubber bar is attached to the other material which has higher stiffness, it is hard to bend them together.

Figure 4.16 Piezoelectric Actuation Setting in IntelliSuite

Figure 4.17 The Variation of Deflection of the Silicon Diaphragm in Piezoelectric Actuation

4.2 The Pressure Drops

The behavior of non-turbulent, compressible, and barotropic fluid undergoing steady-state motion is governed by the Bernoulli equation:

$$\frac{V^2}{2g} + z + \frac{P}{\rho g} = C \quad (4-13)$$

where g is the gravity acceleration (9.81 m/s^2 or 32.2 ft/s^2), V is the velocity of the fluid flow, and z is the elevation above a reference datum. The constant C remains unchanged along any streamline in the flow, but varies from streamline to streamline.

Consider a flow in a conduit in which its pressure is measured at two different points at a certain distance apart. The wall drag and the change in elevation lead to pressure drops in fluid flow. For a frictionless flow, the momentum and energy equations are reduced to the same equation – the Bernoulli equation. To calculate the pressure drop and flow rates in a section of conduit from point 1 to point 2, the result can be obtained by applying Bernoulli's equation with input parameters. (Janna, 1993)

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 \quad (4-14)$$

Moreover, A fluid passing through an orifice constriction will experience a drop in pressure across the orifice. This pressure change can be calculated by the following equation (Ulrich J. et al, 1995)

$$\Delta P = \frac{12\eta l \phi}{by^3} \quad (4-15)$$

where η is the viscosity of fluid flow, ℓ is the length of the path, ϕ is the flow rate of the flow, b is the width of the path, and y is the height of the orifice.

In the microvalve under consideration, the flow conduit is divided into four constrictions and pressure drops in the flow take place when the fluid passes each of these constrictions. Those constrictions are identified in Figure 4.18.

Figure 4.18 The Distribution of Four Constrictions for Pressure Drop Calculation

In constriction I, Equation (4-14) is applied to compute the pressure drop, as:

$$\begin{aligned}\Delta P_I &= \frac{1}{2} \rho (V_2^2 - V_1^2) + \rho g (z_2 - z_1) \\ &= \frac{1}{2} \times 1.2 \times (0.0708^2 - 0.0528^2) + 1.2 \times 9.81 \times 25 \times 10^{-6} \\ &= 1.63 \times 10^{-3} \text{ Pa}\end{aligned}$$

The velocities, V_1 and V_2 can be found in Appendix A.

Other symbols are defined in the previous paragraph.

In constriction II, three kinds of pressure drop conditions exist. First, when the flow enters from constriction I to constriction II, velocity difference, friction loss, and minor loss e.g., induced by the turning of the direction of flow result in the pressure drop situation. Friction losses are due to friction of the gas in contact with the sides of the duct. The head loss due to friction can be expressed as follows: (Janna, 1993)

$$\Delta P_f = f \frac{L}{d} \frac{(V)^2}{2} \rho \quad (4-16)$$

where ΔP_f = head loss due to friction, L = length of duct, d = diameter of duct, V = velocity of gas, f = nondimensional friction coefficient, and ρ = density of gas

Minor losses are due to flow through valves or fitting in a pipeline. This loss can be expressed in terms of a loss coefficient K : (Janna, 1993)

$$\Delta P_v = -K \frac{\rho V^2}{2} \quad (4-17)$$

where ΔP_v = velocity head loss, V = velocity of gas, K = nondimensional friction coefficient, and ρ = density of gas.

The velocity head is not an important factor due to low velocity in this study, so only the head loss due to friction will be considered. (Avallone et al., 1996) Thus, the pressure drop due to the velocity difference from leaving constriction I to entering constriction II is computed as follows:

$$\begin{aligned} \Delta P_{II} &= \frac{1}{2} \rho (V_3^2 - V_2^2) \\ &= \frac{1}{2} \times 1.2 \times (0.3^2 - 0.0708^2) \\ &= 0.05 Pa \end{aligned}$$

The velocity, V_3 can be found in Appendix A.

Second, the flow condition in this constriction is like the orifice flow, since the height of that layer is about 22 μ m. The pressure drop for this part can be calculated from Equation (4-15), but the width of the path in this study varies with the radius. The practical geometry for gas orifice flow in this chamber is illustrated in Figure 4.19.

Figure 4.19 The Practical Geometry for Gas Orifice Flow in the Chamber

The average radius is selected for calculating the width of the path, from which the pressure drop can be computed as below:

$$\Delta P_{II}^* = \frac{12\eta l \phi}{by^3} = \frac{12 \times 18 \times 10^{-6} \times 600 \times 10^{-6} \times 3.33 \times 10^{-8}}{2\pi \times 500 \times 10^{-6} \times (22 \times 10^{-6})^3} = 129 Pa$$

The last component in pressure drop is due to the velocity difference and minor loss. According to the Bernoulli's equation, the other pressure drop can be calculated by the equations below. In this research, the shape of the conduits for gas flow is similar to that of a rectangular duct. For two-dimensional laminar flow through a rectangular duct, in which the width of the conduit is far greater than the height of the conduit, the friction coefficient can be approximated by using the following expression: (Janna, 1993)

$$f = \frac{96}{Re} \quad (4-18)$$

In this study, the ratio of the width to the height of the designed conduit is high enough to justify the use of this equation.

For this estimation, the highest Reynolds number is picked for calculation, d is replaced by twice height of the conduit, L is the length of the conduit, and the average

velocity in this conduit is used for computation. Thus, the pressure drop can be computed as follows:

$$\begin{aligned}\Delta P_{II} &= \frac{1}{2} \rho (V_4^2 - V_3^2) + f \frac{L}{D} \frac{\rho V^2}{2} \\ &= \frac{1}{2} \times 1.2 \times (1.208^2 - 0.3^2) + \frac{96}{30} \frac{600 \times 10^{-6}}{44 \times 10^{-6}} \frac{1.2 \times \left(\frac{1.208 + 0.3}{2} \right)^2}{2} \\ &= 15.7 Pa\end{aligned}$$

The Velocity, V_4 can be found in Appendix A.

After the gas passes the chamber, it goes out through this constriction III. In constriction III, the pressure drop due to the change of the velocities is computed as following:

$$\begin{aligned}\Delta P_{III} &= \frac{1}{2} \rho (V_5^2 - V_4^2) \\ &= \frac{1}{2} \times 1.2 \times (5.308^2 - 1.208^2) \\ &= 16.03 Pa\end{aligned}$$

The velocity, V_5 can be found in Appendix A.

The same situation as in constriction I happens in constriction IV. The pressure drop can be easily calculated by the Bernoulli's equation.

$$\begin{aligned}\Delta P_{IV} &= \frac{1}{2} \rho (V_7^2 - V_6^2) + \rho g (z_7 - z_6) \\ &= \frac{1}{2} \times 1.2 \times (0.225^2 - 0.265^2) + 1.2 \times 9.81 \times (-25 \times 10^{-6}) \\ &= -0.012 Pa\end{aligned}$$

The velocities, V_6 and V_7 can be found in Appendix A.

The total estimated pressure drop in the gas flow through the valve is the sum of pressure drops in all four constrictions as shown below:

$$\begin{aligned}
 Total\Delta P &= \Delta P_I + \Delta P_{II}' + \Delta P_{II}'' + \Delta P_{II}''' + \Delta P_{III} + \Delta P_{IV} \\
 &= 0.00163 + 0.05 + 129 + 15.7 + 16.03 - 0.012 \\
 &= 160.77 Pa
 \end{aligned}$$

One observation can be found from the above result. The pressure drop mainly results from the orifice flow, and other pressure drop sources are so small that can be ignored. This total pressure compared to the designed operating pressure (1.013×10^5 Pa) is not significant. The estimated pressure drop between the inlet and outlet represents the threshold pressure that is required to maintain the gas flow in the valve.

4.3 Power Consumption

Every MEMS device requires supply of power to provide functional operations. Inappropriate power supply not only affects the performance of the device, but it also may cause damage to the device. Therefore, a suitable power supply is a key feature in the design of MEMS devices.

Low power consumption is a highly desired design factor in MEMS. The operating cost of the system and the unnecessary overheating of the components can be alleviated by low power consumption. Low frequency for changing the source of power supply such as batteries also reduces impairment to devices. (Hsu, 2002)

Electricity is a common energy resource in MEMS because it is a convenient means to be used. For power consumption calculations, several simple electrical principles will be discussed in this section.

Based on Equation (4-19), power is defined as the energy consumed at a certain time period Δt .

$$P = \frac{U}{\Delta t} \quad (4-19)$$

Thus, time is a critical factor to determine the power consumption. Figure 4.20 illustrates one working circle for the designed microvalve. The energy will be supplied to open the valve and maintain the valve open in a fully opened position for a desired period of time, to be followed by a time period to the fully closed situation. These three time periods are represented by t_1 , t_2 , and t_3 respectively in Figure 4.20

However, the flow rate depends on the actual requirement. If the required flow rate is very small, the effect of response and closing times needs to be accurately accounted for. On the other hand, if the time for maintaining the valve fully opened is much longer than that for opening and closing of the valve, then the small response time and closing time can be ignored in power consumption estimation.

Figure 4.20 One Working Cycle in the Designed Valve

4.3.1 Response Time for the Designed Micorvalve

There is no such device as a perfect actuator or sensor that is capable of instant response. There always exists a duration of time for devices to be triggered. (Soloman, 1999) The response time of each actuation method is critical for estimating power consumption because the energy consumption for actuation includes the energy for devices to respond. The longer the response time, the higher the total energy consumption is required. If the working frequency is low, a short response time can be ignored in energy consumption estimation. Thus, it is important to check the response time for each actuation mechanism used in this design before the power consumption is estimated. The closing time of the designed valve does not affect the power consumption estimation, but the length of the closing time has an effect on the flow rate.

4.3.1.1 Response Time for Thermal Actuation

The response time of thermal actuation can be estimated by the Equation (4-20). The left-hand side of the equation represents the change in internal energy of total mass of the valve during Δt , and the right-hand side of the equation represents the heat flow from the aluminum plate to the same mass being heated during Δt . (Kreith et al, 1993)

$$c\rho V\Delta T_1 = kA \frac{dT_2(x)}{dx} \Delta t \quad (4-20)$$

where c is the specific heat ($\text{J/kg}^\circ\text{C}$), ρ is the density of mass (kg/m^3), V is the volume of mass, ΔT_1 is the temperature difference between the initial state and the final state, k is the thermal conductivity of the material, A is the surface area of mass, $T_2(x)$ is a function of the temperature change during time interval Δt (sec), and x is the distance for heat to be transferred.

From Figure 4.5 and the temperature result profile by simulation, $T_2(x)$ that is represented in Figure 4.21. The horizontal axis represents the depth from the top surface of the heated aluminum to the attached silicon diaphragm.

Figure 4.21 Temperature Variation in the Depth Direction from the Top Surface

Thus, three periods of time response for each part of heat conduction in Figure 4.21 are estimated by Equation (4-20). The linear variation of temperatures across the thickness of the aluminum and SiO_2 films, and the silicon diaphragm justifies the replacement of “differential” in Equation (4-20) by “differences” as in the subsequent computations.

$$m_{Al} c_{Al} \Delta T = k_{Al} A \frac{\Delta T}{\Delta x} \Delta t_1$$

$$4.03 \times 10^{-6} = 236 \times \pi (325 \times 10^{-6})^2 \frac{30 - 29.5439}{1 \times 10^{-6}} \Delta t_1$$

$$\therefore \Delta t_1 = 1.13 \times 10^{-7} \text{ sec}$$

$$m_{SiO_2} c_{SiO_2} \Delta T = k_{SiO_2} A \frac{\Delta T}{\Delta x} \Delta t_2$$

$$6.15 \times 10^{-7} = 1.4 \times \pi (325 \times 10^{-6})^2 \frac{29.5439 - 25.895}{300 \times 10^{-9}} \Delta t_2$$

$$\therefore \Delta t_2 = 1.09 \times 10^{-7} \text{ sec}$$

$$m_{si} c_{si} \Delta T = k_{si} A \frac{\Delta T}{\Delta x} \Delta t_3$$

$$7.65 \times 10^{-6} = 157 \times \pi (325 \times 10^{-6})^2 \frac{25.895 - 24.9828}{25 \times 10^{-6}} \Delta t_3$$

$$\therefore \Delta t_3 = 4.02 \times 10^{-6} \text{ sec}$$

Consequently, the total response time can be summed up from the above three time

Delays to be:

$$\Delta t = \Delta t_1 + \Delta t_2 + \Delta t_3$$

$$= 1.13 \times 10^{-7} + 1.09 \times 10^{-7} + 4.02 \times 10^{-6}$$

$$= 4.24 \times 10^{-6} \text{ sec}$$

The estimated response time for thermal actuation is about 4.2 μ s.

4.3.1.2 Response Time for Electrostatic Actuation

The actuator size and configuration as well as the driving electronics are the main factors that affect the response time, so it is not easy to calculate the response time in the electrostatic actuation method. However, several simple observations and calculations can be used to estimate the response time. An approximate estimation of the response time for electrostatic actuation is possible by using an RC circuit. (Kornbluh et al, 2000) The electrostatic forces on the electrodes produce this electromechanical response, so the RC time constant in the circuit of the actuator determines the response time. Thus, the RC time constant is not a limiting factor for most small devices because the RC time constant can be manipulated by the actuator design. However, it is not a fundamental limitation on the speed of response of the technology. (Kornbluh et al, 2000)

For example, Figure 4.22 presents the simplest RC circuit. When the capacitor is charged with the supplied voltage, the voltage across the capacitor increases to the

supplied voltage with the time passes. Equation 4.21 can explain this result. Normally, when the time is equal to $5RC$, the voltage across the capacitor is at 99% of the supplied voltage. (Fraser et al, 1994) Therefore, the amount of time for the capacitor to become fully charged in a RC circuit depends on the values of the capacitor and resistor in the circuit.

(a) The estimation for fully charging time in electrostatic actuation by parallel plates

$$C = 8.85 \times \frac{\pi \times (650 \times 10^{-6})^2}{8 \times 10^{-6}} = 1.468 \text{ pF}$$

The capacitance can be calculated by Equation (4-2). Once the resistance in the circuit is 10^6 Ohm, the time for the voltage across the capacitor achieving to 99% of the supplied voltage is $5RC = 5 \times 10^6 \times 1.468 \times 10^{-12} = 7.34 \times 10^{-6} \text{ sec} = 7.34 \mu\text{s}$. Conversely, if the resistance is too large, it takes longer time to charge the electrode plates.

(b) The estimation for fully charging time in electrostatic actuation by annular comb drive

$$C = 2\pi \times 8.85 \times (2+6) \times 10^{-6} \times \left(\frac{1}{\ln \frac{3}{1}} + \frac{1}{\ln \frac{7}{5}} + \dots + \frac{1}{\ln \frac{443}{441}} \right) \cong 5.48 \text{ pF}$$

The capacitance can be calculated by Equation (4-6). The same estimation method also can be used in this part. Once the resistance in the circuit is 2×10^5 Ohm, the time for the voltage across the capacitor achieving to 99% of the supplied voltage is

$$5RC = 5 \times 2 \times 10^5 \times 5.48 \times 10^{-12} = 5.48 \times 10^{-6} \text{ sec} = 5.48 \mu\text{s}.$$

$$V_c = V \left[1 - \exp\left(-\frac{t}{RC}\right) \right] \quad (4-21)$$

At $t=0$
 $Q=0$
 $V_c=0$
 $V_R=V$
 $I=V/R$

At $t=\infty$
 $Q=CV_c$
 $V_c \rightarrow V$
 $I \rightarrow 0$

Figure 4.22 A Description of the Simple RC Circuit

Thus, it is not difficult to control the response time of electrostatic actuation by designing the circuit, which can be adjusted to the same order of that of thermal actuation.

4.3.1.3 Response Time for Piezoelectric Actuation

The estimation of the response time for piezoelectric actuation is in almost the same situation as for electrostatic actuation. The RC time constant also can be controlled by designing the circuit of the designed actuator.

However, the other factor that contributes to time delay results from the inherent response mechanism of the piezoelectric thin layer. Since the piezoelectric layer is thin, this spread time can be less than a millionth of a second. Also, the dielectric constant of the materials does not change significantly over the range of 100 Hz to 100 kHz.

(Kornbluh et al, 2000)

In a previous literature, the response time was reported 1ms in (Judy et al. 1990), but the volume of the PZT part used in that report is much larger than that on the present case. It has 25.4 mm in length, 12.7 mm in width, and 1.6 mm thick. On the contrary, the piezoelectric film in the present case is 5 μm thick with 700- μm radius. In addition, the response time in (Higuchi et al., 1987) is around 6 ms, but its driven mass of the slider is 1.45 kg and the length of the slider is 75 mm that was huge in comparison to the valve in the present design. Since the configuration in this design is simple, the response will much shorter than those mentioned above because of low mass, and thus low inertia forces that results in a much faster deformation of the piezoelectric material. (Higuchi et al., 1990)

Consequently, the response time from our small mechanism of the piezoelectric thin diaphragm can be expected to be very small. Also, the RC time constant in the circuit of designed actuator can be adjusted to provide fast response as the other two actuation methods if a need arises.

4.3.2 Energy Consumption Estimation

From Section 4.3, the definition of the power is the energy consumption during a certain time period. The required time period for valve opening is the same for valves with all three actuation mechanisms for a common design parameter on flow rate. Energy consumption estimation is thus necessary for comparing the power consumptions in these actuation methods. The energy consumption for each actuation method is discussed in the following sections.

4.3.2.1 Energy Consumption for Thermal Actuation by Electric Resistance Heating

According to computations presented in section 4.1.1, a 1- μm thick aluminum plate with a radius of 325 μm is selected as the heat resource to provide the thermal force needed for the actuation of the silicon diaphragm. The voltage will be applied to the surface of the aluminum plate to generate the required heat for the actuation. The energy required for actuation is estimated by calculating the heat provided by thin aluminum. The heat is transferred through silicon dioxide film to silicon diaphragm to generate the required deformation. The energy for thermal actuation is expressed as

$$U = m \cdot c \cdot \Delta T \quad (4-22)$$

where U is the required heat (energy), m is mass being heated (kg), c is the specific heat ($\text{J/kg}^\circ\text{C}$), and ΔT ($^\circ\text{C}$) is the temperature difference before and after the heating.

From the above equation and Figure 4.20, the energy requirement in this case is:

$$\begin{aligned} U &= U_{Al} + U_{SiO_2} + U_{Si} \\ &= m_{Al} c_{Al} \Delta T + m_{SiO_2} c_{SiO_2} \Delta T + m_{Si} c_{Si} \Delta T \\ &= [\pi \cdot (325 \times 10^{-6})^2 \times 1 \times 10^{-6} \times 2700] \times (0.942 \times 10^3) \times \left(\frac{30 + 29.5439}{2} - 25 \right) \\ &\quad + [\pi \cdot (325 \times 10^{-6})^2 \times 300 \times 10^{-9} \times 2270] \times (1 \times 10^3) \times \left(\frac{29.5439 + 25.895}{2} - 25 \right) \\ &\quad + \left\{ [\pi \cdot (783 \times 10^{-6})^2 \times 3 \times 10^{-6}] + \pi \left(\frac{(325 \times 10^{-6})^2 + (200 \times 10^{-6})^2}{2} \times 22 \times 10^{-6} \right) \right\} \\ &\quad \times 2300 \times 700 \times \left(\frac{25.895 + 24.9828}{2} - 25 \right) \\ &= 4.03 \times 10^{-6} + 6.15 \times 10^{-7} + 7.65 \times 10^{-6} \\ &= 1.23 \times 10^{-5} \text{ Joule} \end{aligned}$$

After the response time and energy consumption of thermal actuation being calculated, the estimated applied voltage for thermal actuation by electric resistance heating is 0.277V. The detail calculation process is shown in Appendix B.

4.3.2.2 Energy Consumption for Electrostatic Actuation by Parallel Plates

For electrostatic actuation by parallel electrode plates, capacitance is another essential component needed to be evaluated. Since capacitance is related to the electrostatic forces that are required to drive micro motors and actuators, it can be treated as a form of energy stored in an electrostatic field produced by an applied voltage. This energy can be calculated by the data and the equation presented in Section 4.1.2.1 and as shown below. We will first evaluate the capacitance in the pair of aligned plate electrodes:

$$C = 8.85 \times \frac{\pi \times (650 \times 10^{-6})^2}{8 \times 10^{-6}} = 1.468 \text{ pF}$$

The corresponding energy storage is obtained by equation (4-3)

$$U = -\frac{1}{2}CV^2 = -\frac{1}{2} \times 1.468 \times 10^{-12} \times 97^2 = -6.91 \times 10^{-9} \text{ Joule}$$

where the negative sign represents the consumption of energy.

4.3.2.3 Energy Consumption for Electrostatic Actuation by Annular Comb Drive

As mentioned in Section 4.1.2.2, the number of required cylindrical capacitor pairs is 56, and the value of the capacitance changes with the inner and outer radius of each cylindrical capacitance pair is given by Equation (4-6). We will thus have:

$$C = 2\pi \times 8.85 \times (2+6) \times 10^{-6} \times \left(\frac{1}{\ln \frac{3}{1}} + \frac{1}{\ln \frac{7}{5}} + \dots + \frac{1}{\ln \frac{443}{441}} \right) \cong 5.48 \text{ pF}$$

The consumed energy by this actuation method is also can be obtained by Equation (4-7):

$$U = -\frac{1}{2}CV^2 = -\frac{1}{2} \times 5.48 \times 10^{-12} \times 65^2 = -1.16 \times 10^{-8} \text{ Joule}$$

where the negative sign represents the consumption of energy.

4.3.2.4 Energy Consumption for Piezoelectric Actuation

For most applications in MEMS, it is desirable to use piezoelectric materials that have a large piezoelectric coefficient, high electric resistance, low internal voltage and high mechanical stability. As mentioned in Section 4.1.3, PZT piezo crystal is used. The voltage applied to the top and bottom face of the circular piezoelectric film generates the required actuation forces. Thus, the principle for calculating the energy consumption is the same as mentioned in Section 4.3.1. The difference between these two kinds of capacitances is the isolation medium. Air is the isolation medium for electrostatic actuation in 4.1.1, and piezoelectric material is the one for piezoelectric actuation. Thus, relative dielectric constant K is added to equation to calculate the capacitance.

$$C = K\epsilon_0 \frac{A}{d} = K\epsilon_0 \frac{\pi r^2}{t} \quad (4-23)$$

where r is the radius of the piezoelectric film, and t is the thickness of the film.

$$C = K\epsilon_0 \frac{\pi r^2}{t} = 1000 \times 8.85 \times 10^{-12} \times \frac{\pi \times (700 \times 10^{-6})^2}{5 \times 10^{-6}} = 2.72 \times 10^{-9} \text{ Coulomb / volt}$$

Similarly, The energy consumption can be calculated by equation (4-3)

$$U = -\frac{1}{2}CV^2 = -\frac{1}{2} \times 2.72 \times 10^{-9} \times (4.4)^2 = -2.63 \times 10^{-8} \text{ Joule}$$

where the negative sign represents the consumption of energy.

4.3.3 Estimated Power Consumption

Based on a condition of equal time for keeping the valve totally open, the response time for each actuation is kept under a certain small value of several μs . Also, if the time for maintaining the valve open is longer than the opening time, the power consumption during the small response time can be ignored in the total power consumption estimation.

We will find that during a certain actuating time, the power consumption for electrostatic and piezoelectric actuations is low. Thermal actuation consumes the most energy during the same actuating interval.

5.0 Fabrication Processes

The process involved in the fabrication of MEMS devices is similar in nature to the process used in the integrated circuit industry. The difference is that MEMS are mechanical devices which need to be freely moved in a 3D space. For the conventional mechanical fabrication process, the products are made by machining, forging, welding, casting, molding, stamping, etc. However, none of those traditional fabrication techniques can be used in manufacturing MEMS products at this point because of the small dimensions. The fabrication of MEMS must be in a specialized process with equipment and machinery that can perform the requirements in very extreme thermal, baric, and chemical environments. The equipment that can sustain the processes involving harsh environment requirements must also be extraordinarily accurate with high resolution.

Although the design and packaging of the microelectronics are different from those used in MEMS, the materials applied in microelectronics can be used in MEMS due to their dimensional stability and micro fabrication and packaging techniques that are sufficiently mature. (Hsu, 2002)

Intrinsic to the selected processes is the selection of materials that the MEMS devices are to be produced. The predominate materials in this design are:

Substrate: Si<100>, Si<110>, Si<111>, Poly-Si, GaAs, Sapphire, Quartz, Alumina

Interconnects: Al, Au, Ag, Cu, Chrome

Mask materials: Silicon carbide, Silicon nitride

Other insulation materials: Silicon dioxide, Silicon nitride (Griego, et al, 2000)

These and other uncommonly used materials such as quartz and Pyrex, plastics and ceramics can be used in MEMS design. Especially the materials with specific electrical, mechanical and thermal properties can be exploited to achieve the desired results with the specific geometries.

After the materials are selected and the mechanical design is performed, the fabrication processes are carefully considered. Essentially the entire fabrication is nothing more than the bulk micromachining, surface micromachining, and LIGA process of the chosen material in specific patterns. To perform these steps is not trivial. Each step is very dependent on the operating conditions of the apparatus, skill and knowledge of the technicians and the overall effectiveness of the MEMS design.

This is the challenge of designing MEMS devices: simultaneous consideration of all aspects of the design including mechanical, material, fabrication, system integration, electrical, vibration effects, loading, and thermal effects to mention. These are important to all engineering endeavors but seem to be more pronounced in MEMS design. This is due to the fact that the geometries of MEMS devices that we have to work with are all small in scale. Those effects in MEMS design may perform several effects at the same time. (Griego, et al, 2000)

In this study, the following sequence of steps is proposed as one possible fabrication procedure to produce this designed microvalve. These fabrication procedures only demonstrate the general concepts by showing the important steps. Thus, no details are discussed in this Section.

5.1 Fabrication of Valve Body

The valve body is constructed with two parts. These parts are common for three different actuation methods. One part of the valve body is called the bottom part, and the other part is the top part with the boss. Figure 5.1 shows the silicon substrate cut from a larger round Si wafer. The proposed fabrication involves the following steps.

Step 1: Die selection

Figure 5.1 Silicon Die Normal to the $\langle 100 \rangle$ Orientation

Silicon with (100) plane is selected for the valve body as Figure 5.1 shows, since Silicon $\langle 100 \rangle$ is standard substrate material that is also inexpensive. Dies, or substrates in MEMS, are normally cut from 4" wafers with standard 750 μm thickness. The 25 μm thickness of the valve body is chosen for this design. "Wafer dicing" can be cut by diamond/resin saw. The numbers of dies are based on the thickness of the saw blade (50 μm space is needed for 20 μm thick saw blade). An estimated 1700 dies can be obtained from a 4" wafer. Other sizes of wafers (6" or 8") will work for this case as long as the equipment can accommodate larger wafers.

Step 2: Substrate cleaning

In this step, Pirahna method is employed to get cleaner working surface. A liquid containing H_2SO_4 75% and H_2O_2 25% will be used for 10 minutes to do cleaning.

Step 3: Wet Etch with $\text{KOH}_{(\text{aq})}$

A wide variety of etchants have been used for anisotropic etching of silicon. The alkaline aqueous solutions of KOH , NaOH , LiOH , CsOH , NH_4OH , etc. are the etchants. Comparisons of principal characteristics of different anisotropic etchants are presented. (Madou, 1997). $\text{KOH}_{(\text{aq})}$ is used in the present case because this etchant is simple to use. Also, the KOH etchant provides a uniform and smooth surface at 80°C in near saturated solutions (1:1 in water by weight). In general, a typical wet anisotropic etch rate for Silicon $\langle 100 \rangle$ with $\text{KOH}_{(\text{aq})}$ is $1.1 \mu\text{m}/\text{min}$. It will take only about 20 minutes to finish this step.

Figure 5.2 The Final Configuration of the Bottom Part of the Valve Body

Mask material selection is also important for the etching process. SiO_2 is not a good choice for mask in $\text{KOH}_{(\text{aq})}$, since the etching selectivity between Si and SiO_2 is not sufficiently high to warrant a quality product. Thus, Silicon nitride (Si_3N_4) is selected as the mask material. Its high resistance to many etchants makes it suitable for the mask for

deep etching. (Madou, 1997) Figure 5.2 shows the final configuration of silicon die for the bottom part of the valve body after $\text{KOH}_{(\text{aq})}$ etching. The cross section of this part is demonstrated in Figure 5.3.

Figure 5.3 The Cross Section of the Bottom Part of the Valve Body

Step 4: This step is to repeat Step 1 and Step 2 to select the die for top part of the valve body and have it cleaned. The thickness of this die is 25 μm .

Step 5: In this step, $\text{KOH}_{(\text{aq})}$ is also used for wet etching with different mask to get the top part of the valve body as Figure 5.4 shows.

Figure 5.4 The Configuration of the Top Part of the Valve Body after Etching

Step 6: Deposit Si_3N_4 with LPCVD

As mentioned before, silicon nitride is a commonly used material in IC circuits due to its many excellent chemical, electrical, and mechanical properties. In this step, 1~2 μm thick silicon nitride is deposited to the bottom of the boss by LPCVD method.

Si_3N_4 is deposited by LPCVD at 700~900 $^{\circ}\text{C}$, and functions as an oxidation mask and a gate dielectric in IC industry. In micromachining, LPCVD silicon nitride serves as an important mechanical membrane material and insulation layer. In this design, this extra film can solve sealing problem using a line contact. Due to high frequency movements of the part with boss, the stiffness of this film is also extremely critical. Thus, the Young's modulus of Si_3N_4 is high enough to provide a good choice for this application. The blue part of Figure 5.5 shows the Si_3N_4 film.

Figure 5.5 The Final Configuration of the Top Part of the Valve Body with Si_3N_4 Film

Step 7 Valve body assembly

Because sealing is a serious problem in microvalve, when the top part of the valve body is attached to the bottom one, source of sealing problem occurs. Thermal silicon fusion bonding (SFB) is used to solve this problem. Thermal silicon fusion bonding is a surface bonding method for bonding two silicon wafers or substrates without the use of

intermediate adhesives. The process making silicon substrate bonded together is simpler than other currently employed bonding techniques. It provides higher adhesive forces but lower cost, and it provides better performance in some applications such as micro pressure sensors and accelerometers.

According to many references, those bonding surface should be undergone hydration, a process that is accomplished by bathing the wafers in an $\text{H}_2\text{O}_2\text{-H}_2\text{SO}_4$ mixture, diluted H_2SO_4 , or boiling nitric acid. After that exposure, those cleaning surfaces can be easily bonded at room temperature. However, higher bonding temperature at $1100^\circ\text{C} \sim 1400^\circ\text{C}$ provides stronger bonding during. (Hsu, 2002, Madou, 1997) Figure 5.6 shows the cross section of the assembly of the valve body.

Figure 5.6 The Cross Section of the Assembly of the Valve Body

5.2 Fabrication of Actuators

The performances and sizes of active MEMS devices depend strongly on the features of the actuator, since each actuation method has different characteristics and requirements. The cost and availability of fabrication for different actuators are also significant. The fabrication processes of different actuators in this design will be discussed in the following sections.

5.2.1 Fabrication of Actuator Using Thermal Actuation

Step1: SiO₂ thin film deposition

As mentioned in 4.1.1, thin SiO₂ thin film is deposited on the top of the valve body to provide insulation from the heating of aluminum film heater. Silicon dioxide is a very important material in microfabrication since it can be easily deposited on the substrate and it provides excellent thermal and electrical insulation. SiO₂ is also a good masking material for wet etching of silicon.

Figure 5.7 SiO₂ Thin Film Deposited by Thermal Oxidation.

In this design, 300-Angstrom thick SiO₂ film is deposited by thermal oxidation, which is the least expensive way. The desired quality and thickness of the SiO₂ film can be achieved by controlling the time, temperature, and gas flow. Figure 5.7 shows the result after SiO₂ is deposited by thermal oxidation.

Step 2: Aluminum Sputtering

In this step, 1 μm thick aluminum film is deposited by sputtering, a process that is often used to deposit thin metallic films in the order of 100 Angstroms onto substrate surface. As mentioned in 4.1.1, thin aluminum film is used as an electrically resistant

heater to cause the deflection of the silicon diaphragm. This movement is possible because of the difference of the thermal expansion coefficients of the two materials.

Aluminum is selected for this thermal actuation because of its high electrical resistivity ($10^{-5.5}\Omega\text{-cm}$), high specific heat ($0.942\text{ J/g }^{\circ}\text{C}$), and high thermal expansion coefficient ($25\times 10^{-6}/^{\circ}\text{C}$) which is about 11 times of that of silicon. Fast response of actuation can be expected with aluminum heaters due to high diffusivity. (Hsu, 2002)

Sputtering, evaporation, and plasma CVD are three possible ways to deposit thin aluminum film as used in the IC industry. (Madou, 1997) Sputtering is preferred over chemical vapor deposition (CVD) processes in many applications for better uniformity of thin films, and for better adhesion. Sputtering also involves low pressure compared to plasma CVD, so little chemical reaction can happen. (Hsu, 2002) Thus, sputtering will be used to deposit this thin aluminum film. Figure 5.8 shows the configuration after sputtering thin aluminum film.

Figure 5.8 The Deposition Result after Aluminum Thin Film Sputtering

Step 3: Cover fabrication

This step repeats Step 1, Step 2, and Step 3 in wet etching with different masks to get a cover that protects the actuation part as in Figure 5.9 shows. The thickness of the silicon substrate is 10 μm , and the depth for etching is 8 μm .

Figure 5.9 The Cover for the Actuator Using Thermal Actuation

Step 4: Assembly for thermal actuation

Silicon fusion bonding (SFB) is used for attaching the cover from Step 3 to the top surface of the component from Step 2. The configuration of this part is illustrated in Figure 5.10. Figure 5.11 presents the final configuration of the assembly designed with thermal actuation.

Figure 5.10 The Configuration of Thermal Actuation Part (Not to Scale)

Figure 5.11 The Assembly of the Deigned Valve with Thermal Actuation (Not to Scale)

5.2.2 Fabrication for Electrostatic Actuation by Aligned Electrodes

Step 1: Copper Sputtering

This step is almost the same as the Step 2 in the previous section. However, the deposited material is Copper instead, which is a good electrical conductor that has a low electrical resistivity ($10^{-5.8} \Omega\text{-cm}$). Thus, Copper is used as the electrode material in this electrostatic actuation design. Sputtering is used to deposit $1 \mu\text{m}$ thick copper film to the top surface of the valve body. The estimated time required for this deposition is 3 minutes. The result is demonstrated in Figure 5.12.

Figure 5.12 The Configuration of $1 \mu\text{m}$ Thick Copper Film Being Deposited

Step 2: Space construction for the other aligned electrode

This step is the same as the Step 3 in the previous section in producing a gap for the other aligned electrode by etching as shown in Figure 5.13. Thickness of this silicon substrate is $15\text{ }\mu\text{m}$, and the depth for etching is $10\text{ }\mu\text{m}$.

Figure 5.13 Space Construction for the Other Aligned Electrode

Step 3: Sputtering of copper for the other electrode

$1\text{ }\mu\text{m}$ thick copper film is to be sputtered to the etched surface of the part in previous step in 3 minutes as Figure 5.14 shows.

Figure 5.14 The Configuration after $1\text{ }\mu\text{m}$ Copper Sputtering for the Other Electrode

Step 4: Assembly for electrostatic actuation by aligned electrodes

Silicon fusion bonding (SFB) is also used for attaching the component from step 3 to the top surface of the component from step 1. The cross section of this part is represented in Figure 5.15. After assembly, appropriate voltage supply will generate the necessary electrostatic forces to pull the silicon diaphragm up and down. Figure 5.16 shows the assembly of the deigned valve with electrostatic actuation by aligned electrodes.

Figure 5.15 The Cross Section of the Electrostatic Actuation Part (Not to Scale)

Figure 5.16 The Assembly of the Deigned Valve with Electrostatic Actuation by Aligned Electrode Plates (Not to Scale)

5.2.3 Fabrication for Electrostatic Actuation by Annular Comb Drive

This process will be incorporated the top part of the valve body described in Section 5.1. When the substrate is selected for the top part of the valve body, the thickness of silicon die is 35 μm , instead of 25 μm as described in Step 4, Section 5.1. The same top part of the valve part can be fabricated by following Step 5 and Step 6 in

Section 5.1. The following procedure will discuss how to fabricate an annular comb drive.

Figure 5.17 The inside Five Concentric Silicon Circles Etched by Dry Etching

Step 1: Dry etching

As mentioned in section 4.1.2.2, the parallel electrodes are required to actuate the diaphragm. Since those annular comb drives need high resolution in thin film structures and vertical sidewalls in the substrate, dry etching is considered. Dry etching is a very powerful technique for fabrication in microsystems. Dry etching is the better alternative particularly for deep anisotropic etching of polymer or silicon, because it provides faster etch rate and profiles control. Reactive ion etching (RIE) is the most common form of dry etching for micromachining applications. The material is removed by the accelerated ions. Because RIE is an anisotropic etching technique, deep trenches and pits (up to ten or a few tens of microns) with vertical walls can be etched in a variety of materials including silicon, oxide and nitride. Unlike anisotropic wet etching, RIE can be used in any crystal planes in the silicon. (Madou, 1997) The 56 concentric annular pairs of electrodes with $8\mu\text{m}$ depth are etched by dry etching with suitable mask made

in Si_3N_4 in 2 minutes. Figure 5.17 represents the inside 5 concentric pairs after this fabrication.

Step 2: Sputtering 300-Angstrom thick copper film to the top surface of the upper electrodes in Figure 5.17. Copper is used as the electrode material to generate the necessary electrostatic forces.

Step 3: This step is the same as Step 3 in Section 5.2.1. It performs wet etching with specific mask to produce the other comb actuation part as shown in Figure 5.18. The thickness of this silicon substrate is $15\text{ }\mu\text{m}$, and the depth for etching is $2\text{ }\mu\text{m}$.

Figure 5.18 The Substrate after Etching with Specific Mask (Not to Scale)

Step 4: In this step, it repeats Step 1 and Step 2 to fabricate the other annular comb drive.

Figure 5.19 shows the inside 5 concentric electrodes without copper sputtering.

Step 5: Assembly for electrostatic actuation by annular comb drive

Silicon fusion bonding (SFB) is used here for attaching the component from that presented in Step 4 to the top surface of the component from Step 2. The configuration of cross section of the comb drive is illustrated in Figure 5.20.

Figure 5.19 The inside Five Concentric Electrodes without Copper Sputtering

Figure 5.20 The Configuration of Part of the Comb Drive Component (Not to Scale)

5.2.4 Fabrication for Piezoelectric Actuation

Step 1: Copper sputtering

A thin copper film of 500-Angstrom thick is deposited to the top surface of the valve body by sputtering as Figure 5.21 shows. This thin copper film is used as the conductor for the applied voltage to actuate the diaphragm of the valve.

Step 2: Piezoelectric material deposition

The working principles for piezoelectric material have been presented in Section 4.1.3. A problem with this type of material is their temperature sensitivity and aging (loss of piezo properties) when approaching the Curie temperature, where the dipole directions in this material have random orientations. (Madou, 1997)

Figure 5.21 The Configuration of 500-Angstrom Thick Copper Film by Sputtering

Figure 5.22 The Configuration of 5 μ m Thick PZT Film by Sputtering

Based on the result of Section 4.1.3, a thin PZT film of 5 μ m thick is deposited to the top surface of the copper film described in the previous step by sputtering. The PZT material can be easily grown in thin-film form in sputtering. (Madou, 1997) Figure 5.22 shows the configuration of this film by sputtering.

Step 3: Copper sputtering for the other conduction layer

This step is the same as Step 1. It is intended to deposit the 500-Angstrom thick copper film as the conductor to the top surface of PZT layer. The latter is fabricated as

described in the previous step.

Step 4: Cover fabrication

This step is the same as Step 3 in Section 5.2.1. It involves wet etching with different mask to produce a cover that protects the actuation part as illustrated in Figure 5.9. The thickness of this silicon substrate is 20 μm , and the depth for etching is 15 μm .

Step 5: Assembly for piezoelectric actuation

Thermal silicon fusion bonding (SFB) is used here for attaching the cover from Step 4 to the top surface of the component from Step 3. The configuration of cross section of this part is illustrated in Figure 5.23. Figure 5.24 shows the assembly of the designed valve with piezoelectric actuation in the IntelliSuite package.

Figure 5.23 The Configuration of the Piezoelectric Actuation Part (Not to Scale)

Figure 5.24 The Assembly of the Designed Valve with Piezoelectric Actuation (Not to Scale)

6.0 Discussion of Results

Section 4 and 5 presented the parameters and issues involving in the design and fabrication of microvalves using three distinct actuation methods. These parameters include applied voltage, power consumption, and specific fabrication processes. The most critical issue is which of these three actuation methods can provide the best performance based on a common basic design configuration of a microvalve body. A comparison of some of these merits will be discussed in this section.

Table 6 The Relationship between Applied Voltage and Power Consumption

Actuation methods	Thermal actuation	Electrostatic actuation		Piezoelectric actuation
		Parallel plates	Annular comb drives	
Applied voltage	0.28V	97V	65V	4.4V
Power consumption	$\frac{1.23 \times 10^{-5}}{\Delta t} W$	$\frac{6.91 \times 10^{-9}}{\Delta t} W$	$\frac{11.6 \times 10^{-9}}{\Delta t} W$	$\frac{26.3 \times 10^{-9}}{\Delta t} W$

Δt : the actuating time (response time and full opening time)

6.1 Applied Voltage and Power Consumption

The relationship between the applied voltage and the power consumption is presented in Table 6 following the computations presented in Section 4.3. The applied voltage for the case of thermal actuation is the smallest, and the power consumption compared with other actuation methods is the highest based on the same actuating time. Moreover, the applied voltage in thermal actuation is too small to be practical, and the voltages for the two cases of electrostatic actuation are much too large for microdevices.

The applied voltage in piezoelectric actuation seems more realistic by conventional batteries. The power consumption by piezoelectric actuation is a little higher than that by both cases of electrostatic actuation methods. From the applied voltage point of view, however, we conclude that piezoelectric actuation is the most optimal method of all.

6.2 Overall Size and Weight

Overall size and actuator weight for these three actuation methods are estimated and compared in this section. Based on the same basic microvalve body, the difference in the overall size and weight of the units depends on the size and weight of the actuation chamber. The geometry of the valve by each actuation method is presented in Section 4 and 5. The assessed height and weight of each actuator is presented in Table 7.

Table 7 Comparison on Actuator Height and Weight in Three Actuation Methods

Actuation methods	Thermal actuation	Electrostatic actuation		Piezoelectric actuation
		Parallel plates	Annular comb drives	
Actuator height	10 μm	15 μm	23 μm	20 μm
Actuator weight	84 μg	115 μg	144 μg	187 μg

From Table 7, the electrostatic actuation by annular comb drives has the largest overall height due to the many concentric annular silicon electrodes required to perform the desired actuation. The case with 5 μm thick PZT film in the piezoelectric actuation has made the overall size of this actuation a little larger than the others. Moreover, the density of PZT thin film (7.8 g/cm^3) is high. Consequently, the weight of the piezoelectric

actuated valve is the highest among the same valves using other actuation methods.

However, these three actuation methods in overall size and weight are too close to be distinct.

6.3 Fabrication Cost

A possible fabrication process for microvalves with each actuation methods is presented in Section 5. The cost of fabrication process for each actuation method will be discussed in this section, as fabrication cost is also an important point we should be concerned with MEMS devices production.

Wet etching and sputtering are used in all actuation methods. Nevertheless, the reactive ion etching (RIE) is used in the electrostatic actuation using annular comb drives, and this technology is more expensive than wet etching. Also, this fabrication process requires high precision equipment and masks during the fabrication. This type of actuated valve also requires high-resolution machine to accomplish the assembly for the upper and lower comb drives. Thus, the cost for fabricating the microvalve with electrostatic actuation by annular comb drive is higher than others. Generally speaking, no significant difference in production cost is expected among all three kinds of actuation methods.

7.0 Conclusions

Relative merits, such as power consumption, overall size and weight, and fabrication cost for microvalve using three different actuation methods are compared in the Section 6. The piezoelectric actuation scores well among these three types of actuation methods, because of its acceptable power consumption with realistic requirement on the supplied voltage, medium overall size and tolerable weight, as well as moderate fabrication cost.

For electrostatic actuation, two forms of actuation method are considered in this study. Although the voltage supply for the electrostatic actuation by annular comb drives is only about 65V, which is $\frac{2}{3}$ of the voltage required for electrostatic actuation by parallel plates, its overall size and fabrication cost are higher than the conventional parallel plates method. However, it provides an alternative configuration for microvalve designers.

Several critical problems are not mentioned in this study, such as packaging, sealing, detail fabrication procedures, and closing time (shut-off time). Packaging is a very complicated and troublesome task in the microdevices. Sealing problem is also important in the micro fluidic systems because this may generate unnecessary leakage. In this design, the elasticity of the silicon diaphragm is expected provide tight sealing of gas flow. Detail fabrication procedures are not mentioned in this thesis. Instead, the purpose of conceptual fabrication steps mentioned in Section 5 is to compare the associate costs. As for the valve closing time, although it does not influence on the power consumption

estimation, it does affect the actual flow rate especially in thermal actuation in which the thermal inertia of the valve may be non-trivial. Assessment of the valve closing time is a major task, which would merit a stand-alone thesis research.

Another major design consideration is the involvement of liquids as flow media. In such cases, the effects of fluid/solid interactions, such as convective heat transfer and fluid induced forces may become too important to be ignored. These fluid/solid interface problems are not significant in the case of gas flow. Moreover, the stresses and strains that result from the small deformation of the silicon diaphragm are also ignored because of the high yielding stress of silicon.

Appendices

Appendix A: Estimation on Gas Flow Velocities and Reynolds Number in Various Sections of A Microvalve

With fixed flow rate $Q=2$ mL/min and the continuity equation $Q = A_1V_1 = A_2V_2$, (Janna, 1993) the velocities of each entries and outlets of each constriction can be obtained by applied the continuity equation.

Each velocity and corresponding cross section area are defined as following:

V_1 : the velocity entering the constriction I

V_2 : the velocity leaving the constriction I

V_3 : the velocity entering the constriction II

V_4 : the velocity leaving the constriction II

V_5 : the velocity passing the constriction III

V_6 : the velocity entering the constriction IV

V_7 : the velocity leaving the constriction IV

$$A_1 = \pi(817^2 - 683^2) = 6.31 \times 10^5 \mu m^2$$

$$A_2 = \pi(800^2 - 600^2) = 4.71 \times 10^5 \mu m^2$$

$$A_3 = 2\pi r_o \times h = 2\pi \times 800 \times 22 = 1.11 \times 10^5 \mu m^2$$

$$A_4 = 2\pi r_i \times h = 2\pi \times 200 \times 22 = 2.76 \times 10^4 \mu m^2$$

$$A_5 = 2\pi r_i \times h = 2\pi \times 200 \times 5 = 6.28 \times 10^3 \mu m^2$$

$$A_6 = \pi \times 200^2 = 1.26 \times 10^5 \mu m^2$$

$$A_7 = \pi \times 217^2 = 1.48 \times 10^5 \mu m^2$$

Thus, each velocity can be computed as following:

$$V_1 = \frac{Q}{A_1} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{6.31 \times 10^5 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 0.0528 \frac{m}{sec}$$

$$V_2 = \frac{Q}{A_2} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{4.71 \times 10^5 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 0.0708 \frac{m}{sec}$$

$$V_3 = \frac{Q}{A_3} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{1.11 \times 10^5 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 0.3 \frac{m}{sec}$$

$$V_4 = \frac{Q}{A_4} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{2.76 \times 10^4 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 1.208 \frac{m}{sec}$$

$$V_5 = \frac{Q}{A_5} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{6.28 \times 10^3 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 5.308 \frac{m}{sec}$$

$$V_6 = \frac{Q}{A_6} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{1.26 \times 10^5 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 0.265 \frac{m}{sec}$$

$$V_7 = \frac{Q}{A_7} = \frac{2 \times 10^{-6} \frac{m^3}{min} \times \frac{1}{60} \frac{min}{sec}}{1.48 \times 10^5 \mu m^2 \times 10^{-12} \frac{m^2}{\mu m^2}} = 0.225 \frac{m}{sec}$$

In the constriction II, the maximum velocity is V_4 that results in the max Reynolds number is

$$R_e = \frac{\rho v L}{\mu} = \frac{1.2 \frac{kg}{m^3} \times \left(\frac{0.3 + 1.208}{2} \right) \frac{m}{sec} \times 600 \times 10^{-6} m}{18 \times 10^{-6} \frac{N \cdot sec}{m^2}} = 30.16 < 100$$

where ρ is the density of air, v is the average velocity (V_3 and V_4) in constriction II of the gas flow, L is the gas travel length, and μ is dynamic viscosity of air.

Appendix B Estimated Applied Voltage for Thermal Actuation by Electric Resistance Heating

According to the definition of electric current, $I = \frac{dQ}{dt}$, we may express the power

in an electric circuit from Equation (4-19) to be:

$$P = IV = I^2 R = \frac{V^2}{R} \quad (\text{B-1})$$

where P is in watt, I is in amp, V is in volts, and R is in Ohm.

Since the electric voltage is applied to the top surface of the aluminum film, the resistance is estimated by the following equation:

$$R = \frac{\rho L}{A} = \frac{2.65 \times 10^{-8} \times 325 \times 10^{-6}}{325 \times 10^{-6} \times 1 \times 10^{-6}} = 2.65 \times 10^{-2} \Omega \quad (\text{B-2})$$

in which ρ is the resistance constant for aluminum, L is the length of the current passes, and A is the cross section area for the current

Based on Equation (B-1), the required applied voltage becomes:

$$\frac{U}{\Delta t} = P = \frac{V^2}{R}$$

$$\text{Thus, } V = \sqrt{\frac{U}{\Delta t} \times R} = \sqrt{\frac{1.23 \times 10^{-5}}{4.24 \times 10^{-6}} \times 2.65 \times 10^{-2}} = 0.277V$$

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