Valveless piezoelectric micropump of parallel double chambers

Li Guo, Weiping Yan#, Yinghua Xu, Yiru Chen

School of Electronic Science and Technology, Dalian University of Technology, Dalian 116024, China
Corresponding Author / E-mail: yanwp@dlut.edu.cn, TEL: +86-411-8470-7428, FAX: +86-411-8470-6706

KEYWORDS : Valveless micropump, MEMS, ANSYS, Piezoelectric actuator

The driving performance of the piezoelectric actuator was simulated by ANSYS software, and the relationship between structure parameters and center displacement / frequency of piezoelectric actuator were obtained. The nozzle/diffuser pipes' structure parameters were optimized according to the results of ANSYS numerical simulation, and flow characteristic parameters such as flow rate and pressure distribution in the pipe were researched. The chamber was manufactured on glass, and nozzle/diffuser pipes were fabricated on <100> silicon by selective-wet etch using MEMS technology. These two components were glued with piezoelectric actuator together to form micropumps with single chamber and micropumps with parallel double chambers. The flow rates of micropumps in different conditions were measured by test system. Finally, a comparison between the test results of micropump with double chambers and that of the single chamber micropump is given.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

ρ = density
σ = poisson's ratio
E = flexibility modulus
SCP = single chamber pump
DCP = double chambers pump

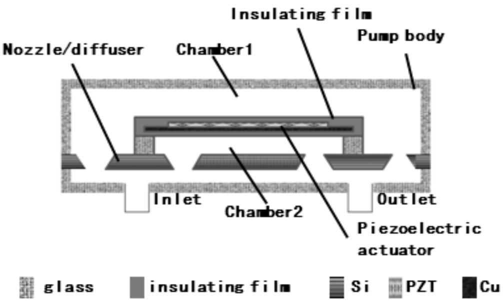
1. Introduction

A miniaturized laboratory (lab-on-a-chip) must be able to handle fluids with a wide variety of properties, i.e. viscosity, density, ion strength, pH, temperature, and surfactants. The precision of fluid properties is dependent on the micropump used for fluid driving [1]. So micropumps are essential components in microfluidic analysis systems. Today micropumps have been suggested for use in applications where small size and accurate flow volume control are essential. Typical applications are implanted medical drug delivery systems [2], microchemical and biological analysis instruments [3], and microfluid chemical resistance systems [4]. Many novel pumping strategies such as pumps based on growing and collapsing bubbles, electro-hydrodynamics, electro-osmosis and flexural plate waves have also been presented [5]. Most of these micropumps can be made very small and can realize certain functions, but some problems have to be resolved, such as complicated structures, unreliable characteristics, and difficult to make three-dimensional structures [6]. So a novel valveless piezoelectric micropump of parallel double chambers was presented in this paper. To obtain the most efficient structure of the micropump, parameters of piezoelectric actuator and nozzle/diffuser were optimized by Finite Element Analysis software ANSYS. Micropump has been manufactured with MEMS technics, encapsulated and tested. The work supplied valid data to optimize further the structure of micropump.

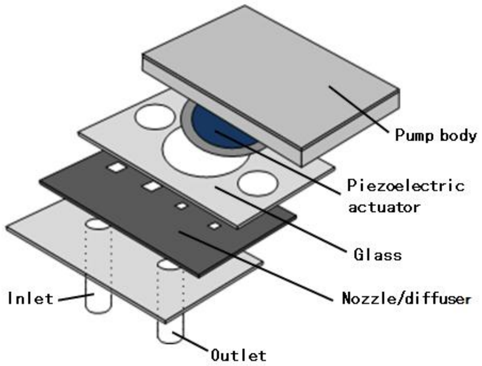
2. Micropump structure design and ANSYS simulation

2.1 Structure design

Valveless piezoelectric micropump of parallel double chambers is presented in this paper, and the structure is shown in Fig.1. The parallel double chambers can avoid pulse flow and generate steady flow. It was manufactured very simply by anisotropic etching in <100> silicon wafer to achieve pipes with the angle was 70.52°and the length was wafer thickness [7], so they can be used for nozzle/diffuser pipes. Piezoelectric actuator was a resonance body combined a hard and brittle piezoelectric ceramic and a thin metal sheet together [8]. Metal sheet used for piezoelectric actuator should be easy processing, good electrical conductivity and flexibility, and common materials are brass, copper and aluminum [9]. So materials of PZT and copper were chosen as piezoelectric ceramic and metal sheet. In order to avoid a short circuit caused by fluid contact with actuator, piezoelectric actuator was deposited a layer of insulating film on the surface. Pump chamber was made of 150μm thickness glass with 13mm diameter circular cavity.



(a)

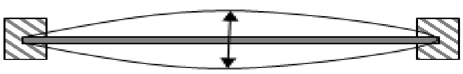


(b)

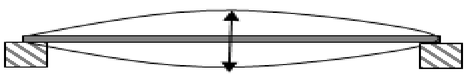
Fig. 1 Structure of micropump including (a) ichnographic view and (b) three-dimensional view.

2.2 Piezoelectric actuator simulation

Supported ways of piezoelectric actuator have a great impact on the maximum displacement and resonant frequency of the actuator. The ways supported the piezoelectric actuator have two forms: simply supported and clamped supported. The condition that the actuator and the pump body are pasted together on only one side is the simply supported, and they contact together on both sides is the clamped supported. The two supported ways are shown in Fig. 2.



(a)



(b)

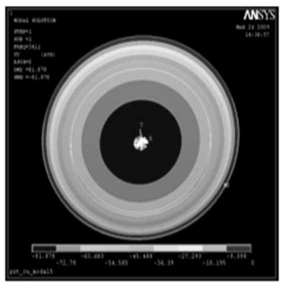
Fig. 2 Two support methods of PZT buzzer, (a) clamped supported condition, (b) simply supported condition.

Piezoelectric effect analysis is a structure - electric field coupled analysis [10]. ANSYS simulation was used to optimize the structure of piezoelectric actuator. A few microns thick layer of paste was ignored, and the piezoelectric actuator was simplified as a natural fit combined with the metal layer and piezoelectric layer. The piezoelectric units and the metal Cu units were selected respectively as SOLID5 and SOLID45, and the material parameters are presented in Table. 1. First of all, PZT layer and Cu layer were established by MESH200 modules. Then they were pasted together by the GLUE command and were meshed. Finally they were expanded to form a three-dimensional actuator model by EXTRUED command. The boundary conditions of piezoelectric actuator were set: PZT was applied coupled voltage field whose voltage was 10V on the upper surface, and the voltage was 0 V on the lower surface. Actuator was supported in the form of simple support and clamped support. The freedom degrees of the nodes on the Cu sheet edge were zero on Y direction when it was simply supported, but they were zero on X, Y, Z direction when it was clamped supported.

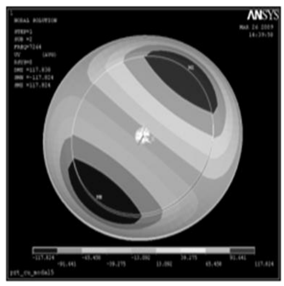
	ρ(kg/m^3)	σ	E(GPa)
Cu	8.96	0.3	118.2
PZT-5	7.6	0.36	/

Table. 1 Material parameters in simulation.

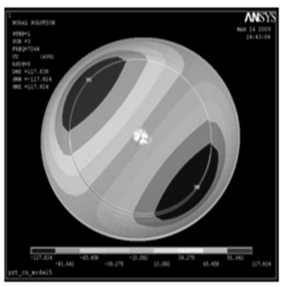
ANSYS modal analysis was used to determine the vibration characteristics of the general machine components and structures. Through the structural modal analysis, modal frequency response and the results of modal expansion analysis could be obtained. They included: the natural frequency, expanded mode shapes, the corresponding strain and force distribution. Modal analysis was not only a very important parameter for structural design under dynamic loading conditions, but also needed in the spectral analysis, harmonic analysis and transient analysis. Through modal simulation of piezoelectric actuator, the first four resonance frequency was obtained under the simply supported condition, which was respectively 3411Hz, 7164 Hz, 7170 Hz, and 13824 Hz. The first four resonance frequency was respectively 6224 Hz, 11915 Hz, 11955 Hz, and 19361 Hz under the clamed supported condition. Vibration modes in simply supported condition were shown in Fig. 3.



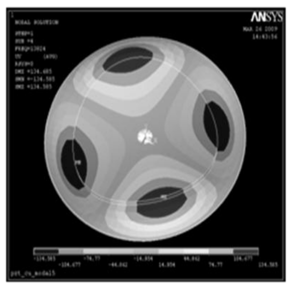
(a) First resonance mode



(b) Second resonance mode



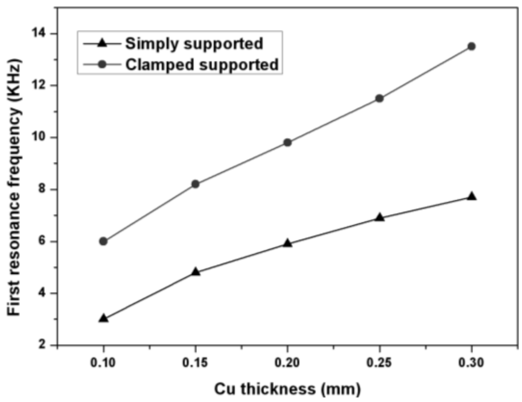
(c) Third resonance mode



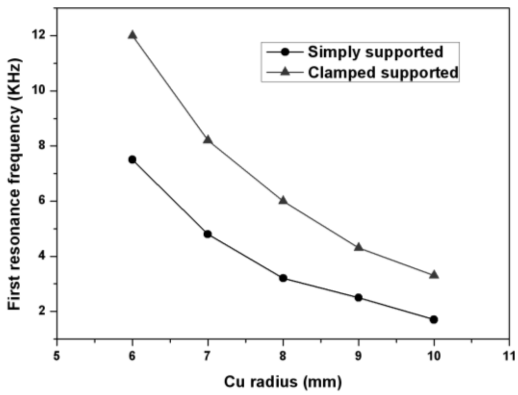
(d) Forth resonance mode

Fig. 3 The first four modal shapes of PZT actuator. The sizes of PZT and Cu respectively are 0.2mm and 0.1mm in thickness, 5mm and 7mm in diameter. The colors on the modal represent the displacement

According to modal simulation of piezoelectric actuator, it was found that the maximum point of vibration displacement located at center of actuator only when piezoelectric actuator was in the first resonance mode. It can be seen that volume of pump chamber changed maximally in the first resonance mode of actuator. So the piezoelectric actuator of pump system should work in the first resonance mode. In ANSYS simulation, the actuator consisted of circular copper sheet and PZT with 0.2mm in thickness and 5mm in radius. The parameters of copper sheet were optimized as to achieve the structure with lower resonant frequency and larger amplitude. In Fig.4, copper sheets with different fixation were compared, and it can be seen that the resonance frequency at simply supported condition were lower than that at clamped supported condition. As Fig. 4(a) shows, as copper sheet becomes thicker, the resonance frequency of actuator is greater. As shown in Fig. 4(b), as copper sheet radius becomes larger, the resonance frequency of actuator is lower when the copper sheet thickness doesn't change.



(a)



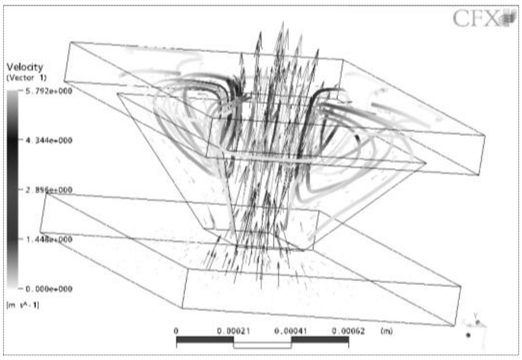
(b)

Fig. 4 Relationship between Cu sheet structure parameter and the first resonance frequency. (a) Curves between thickness and the first resonance frequency, (b) Curves between radius and the first resonance frequency.

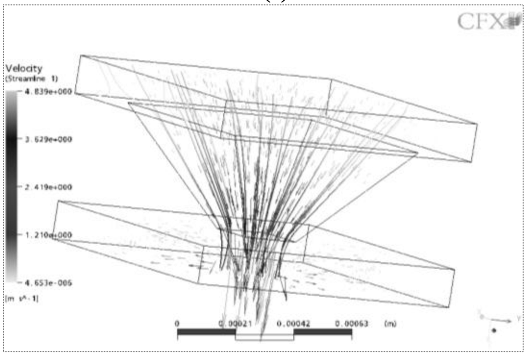
2.3 Nozzle/diffuser simulation

In this paper, ANSYS FLOTRAN and CFX were used for simulation analysis of diffuser / nozzle three-dimension flow field. SST model assembled advantages of the standard model and the equation turbulence model, and it can select the better one between the standard model and the equation turbulence model according to the distance from the wall [11, 12]. It is more suitable for analysis of small Reynolds number turbulence. So the simulation model selected as SST model. Environment parameters in analysis respectively are: reference temperature was 25 ℃; reference pressure was 1 standard atmosphere; fluid density was 1000kg/m^3; viscosity was 0.9×10^{-3}Pa s .The boundary conditions of flow field were set: small end and big end of the nozzle/diffuser were open border, and respectively was applied 0Pa and ± 10000Pa pressure. All of the walls were applied no-slip boundary condition, and their speeds of the three directions all were zero. Fluid was assumed incompressible, and its density and viscosity were constant.

The simulation results given with vector form are shown in Fig. 5. It can be seen in Fig. 5(a), the negative pressure was formed between the fluid and the wall near the lager orifice when it was flowing through the diffuser pipe, so a part of the fluid produced a return and the flow naturally decreased. As shown in Fig. 5(b), the negative pressure was not formed through the nozzle pipe, so it had not the return and the flow was larger than the former.



(a)



(b)

Fig. 5 Vector and flow velocity curve of nozzle/diffuser. (a) The flow in diffuser pipe, (b) The flow in the nozzle pipe.

Since the nozzle/diffuser pipes' angle (75.52°) depended on the structural properties of silicon is constant, so the length and smaller orifice diameter of nozzle/diffuser pipes were presented in ANSYS simulation. In Fig. 6, steady flow rate (difference between flow rate in diffuser pipe and flow rate in nozzle pipe) with different pipe length (380μm, 400μm, 500μm) and diameter is compared at 10000Pa static pressure. It can be seen that the optimum ratio between the length and smaller orifice diameter is 1.9:1 for the maximum flow rate, and the longer the pipe becomes, the better the rectification effect under the optimum ratio is.

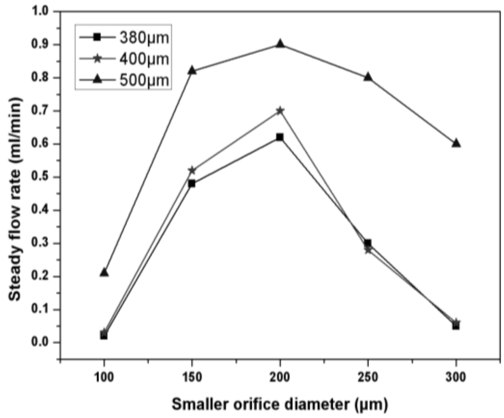


Fig. 6 Curves between steady flow rate and smaller orifice diameter under 10000Pa static press.

In Fig. 7, flow rate curve of 400μm length pipe is presented. It can be seen that the greater the pressure becomes, the larger flow rate difference between nozzle pipe and diffuser pipe is, and the rectification effect becomes better.

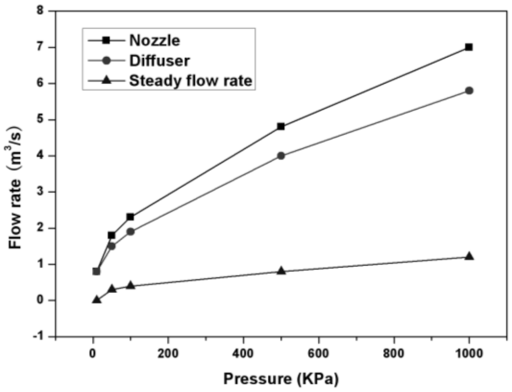


Fig. 7 Curves between flow rate and pressure, the steady flow rate is the difference between the nozzle flow rate and diffuser flow rate.

According to ANSYS simulation, structural parameters of the single chamber micropump was determined: PZT diameter was 10mm and thickness was 0.1mm; copper sheet diameter was 14mm and thickness was 0.1mm; pump chamber diameter was 13mm and depth was 0.15mm; nozzle/diffuser pipe length was 0.4mm, and large orifice diameter was 0.8mm.

3. Fabrication and encapsulation of micropump

The fabrication of micropump was divided into four parts: piezoelectric actuator with PZT and Cu; the diffuser/nozzle with silicon wafer; the pump chamber with glass; the pump body with glass. The diffuser/nozzle was the most essential part, so it was fabricated by MEMS technics. MEMS technics is widely used in various fields, such as the bio-chip, micro-actuators, micro-drive et al., and it can effectively solve the three-dimensional processing problem of various types of materials [13]. MEMS originated in the IC technology, extensive use of IC technology in the lithography, diffusion, dry and wet etching. MEMS technology is processing the vast majority of devices that are three-dimensional devices, so the other manufacturing technology should be applied, for example, sacrificial layer technology, anisotropic etching, and bonding.

The sheet copper was soaked in 15% ~20%dilute hydrochloric acid solution for 1min as to remove the surface oxide layer, and was cleaned by deionized water. Then the sheet copper was glued to PZT by epoxy AB glue and conductive glue, then composed the piezoelectric actuator after laying 24 hours. The electrode of piezoelectric actuator was platinum wire that was 8 mm in diameter. The nozzle/diffuse pipes have been fabricated on 400μm thick and 4inch diameter (100)Si-wafers, its steps included RCA cleaning, thermal oxidation, photoresist apply, alignment and exposure, remove SiO_2, remove glue, wet chemical etching and remove oxide layer. The pump chamber has been fabricated with 150±20μm thick glass that was etched to 13mm diameter chamber as pump chamber by HF solution. The pump body was fabricated by 15mm×15mm×1mm glass slide. Two 2mm diameter holes were drilled distancing 3mm from the center of glass slide by ultrasonic puncher to link the inlet and outlet pipes.

Encapsulation of micropump is a vital step, so every operation must ensure the accuracy and reliability. To achieve better airproof, the air should be removed completely when pump body was glued with inlet and outlet pipes. Next, the silicon wafer with nozzle/diffuser was glued with pump body and pump chamber in turn. At last, the piezoelectric actuator was glued at the top. In order to ensure watertight, it took 24 hours to solidify for the epoxy glue after gluing every layer, and outlet/inlet must be aligned accurately to diffuser/nozzle. Finished micropump is shown in Fig. 8. The size of single chamber micropump is 16mm×16mm×1.5mm, and the size of double chambers micropump is 16mm×22mm×5mm.

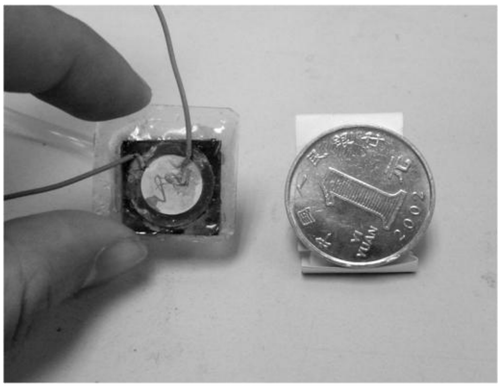


Fig. 8 Photos of finished double chambers micropump, on the left the coin's diameter is 25mm.

4. Experimental results and discussions

The maximum displacement of actuator center was tested under the 100V sinusoidal voltage, and the results are shown in Fig. 9. According to the test results, the first resonant frequency is 3700 Hz, but the simulation result is 3400 Hz. The reason is that the impact of the paste layer was not considered when it was simulated by ANSYS. But the difference between test result and simulation result was not great, and it can be accepted.

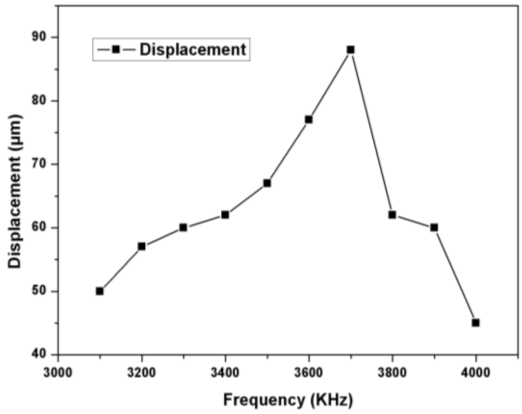


Fig. 9 Curve between the largest displacement of actuator center and the drive voltage frequency.

The SCP and DCP flow rates distribution along frequency have been tested under 110V sinusoidal alternating voltage. The curves are presented in Fig. 10. It can be seen that optimal frequencies of SCP and DCP are different, they are 2600Hz and 2700Hz, respectively. The reason is that glue method of SCP is completely simply supported, but DCP is almost clamped supported. So the optimal frequency of the DCP is larger. The SCP and DCP flow rates distribution along voltage have been measured under optimal frequency. The curves are shown in Fig. 11. It can be seen that as the voltage increases the flow rates of SCP and DCP become larger, and they are almost linear. Under the same voltage, the flow rate of DCP is larger than that of SCP. The maximum flow rate of DCP (151.7μl/min) is about 1.3 times that of SCP (115μl/min) under 110V voltage.

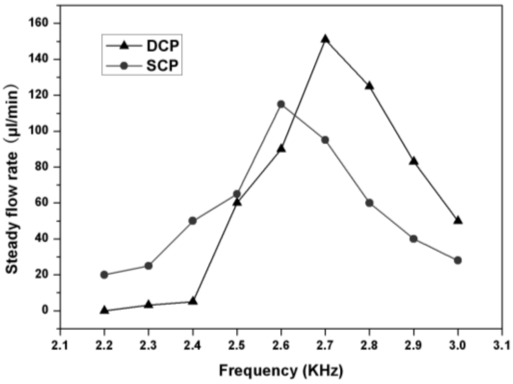


Fig. 10 Curves between SCP and DCP flow rate and frequency.

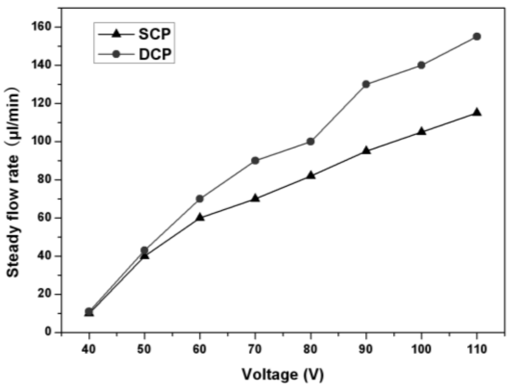


Fig. 11 Curves between the SCP and DCP flow rate and voltage under respective optimal frequency.

Why is flow rate of DCP 2 times that of SCP? Because according to the design for the DCP, volumes of both chambers are not equivalent, and volume of up-chamber is about 2 times that of down-chamber as Fig. 1(a) shows. So the efficiency of up-chamber with larger volume is lower than that of down-chamber with smaller volume under the same condition, and glue method of DCP is almost clamped supported. These factors cause the result that the flow rate of DCP can't reach to 2 times that of the SDP.

5. Conclusions

A novel valveless piezoelectric micropump of parallel double chambers has been presented in this paper and optimized by ANSYS simulation. According to simulation results, volume of pump chamber changes maximally in the first resonance mode of actuator; as the copper sheet thickness increases, the resonance frequency of actuator changes larger; the resonance frequency at simply supported condition are lower than that at clamped supported condition; the optimum ratio between the length and smaller orifice diameter is 1.9:1 for the maximum flow rate. According to the optimized parameter, micropumps of single chamber and double chambers are fabricated by MEMS technics. Test results show that compared with the single chamber pump, double chambers pump improves the energy efficiency of piezoelectric actuator, and the flow rate of the double chambers pump is 1.3 times that of the single chamber pump.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (61074166).

REFERENCES

1. Helene A., Wouter V. W., Peter N., et al., "A Valve-less Diffuser Micropump for Micro-fluidic Analytical Systems," Sensors and Actuators B, vol. 72, pp. 259-265, 2001.
2. Maillefer D., "A High-performance Silicon Micropump for an Implantable Drug Delivery System," the 12th IEEE International Workshop Micro Electromechanical Systems, IEEE Press, pp. 541-546, 1999.
3. Taylor M T, "Simulation of Microfluidic Pumping in a Genomic DNA Blood-processing Cassette," JMM, vol. 13, pp. 201-208, 2003.
4. Dae-Sik L., Jong S. K., and Youn T. K., "Bidirectional Pumping Properties of a Peristaltic Piezoelectric Micropump with Simple Design and Chemical Resistance," Thin solid films, vol. 486, pp. 285-290, 2004.
5. Vishal S., Suresh V. G., Jayathi Y. M., "Low Reynolds Number Flow Through Nozzle-diffuser Elements in Valveless Micropumps," Sensors and Actuators A, vol. 113, pp. 226–235, 2004.
6. Cheng Y. L., Lin J. H., "Manufacture of Three-dimensional Valveless Micropump," Journal of Materials Processing Technology, vol. 192, pp. 229–236, 2007.
7. Hong X., "Introduction to Semiconductor Manufacturing Technology," United States of America: Prentice-Hall inc, 2001.
8. Ivano I., Dino A., Arianna M., et al., "Modeling and Experimental Validation of a Piezoelectric Micropump with Novel No-moving-part Valves," Sensors and actuators a, vol. 133, pp. 128-140, 2007.
9. Wang C. L., Li J. C., and Zhao M. L., "Piezoelectric Ferroelectric Physics," Bei Jing: Science Press, 2009.
10. Wen S. H., Das B., Jiang Y. T., et al., "Simulation of the Diaphragm Properties of a PZT-based Valveless Micropump," the 3rd IEEE Int.Conf.on Nano/Micro Engineered and Molecular Systems, Sanya, China, pp.449-451, 2008.
11. Chen Y. R., Yan W. P., "Study of Valveless Piezoelectric Micropump Based on Parallel Double Chambers," Dalian University of Technology, Dalian, China, 2009.
12. Anders O., Goran S., Erik S., "Numerical and Experimental Studies of Flat-walled Diffuser Elements for Valve-less Micropumps," Sensors and Actuators, vol. 84, pp. 165-175, 2000.
13. Zou Q. B., Wang Z. F., Lin R. M., et al., "A Single-chip Fabrication Technique for Three-dimensional Integrated Fluid Systems," Sensors and Actuators A, vol.72 pp. 115–124, 1999.