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Pre-processing for the Design of Micro-fluid Flow Sensing Elements

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Abstract: A simple finite element analysis is performed to simulate the thermal characteristics of a micro sensor package with thin film heater embedded in the glass wall of a micro-channel. In this paper, Electric characteristics of ITO sputtered heater were presented in this study, which can be used as a map of heater design in the range of available system temperature. The effects of thermo-physical properties of materials, geometrical structure and boundary condition on the thermal performance are also investigated. Finally, the design of micro-flow induced thermal sensor that is capable of measuring fluid flow with a lower flow detection limit of approximately 24pL/s is presented.

Keywords: microchannel, microheating, ITO, sputtered heater, PDMS

1. Introduction

The emerging technology of micro-fabrication in MEMS has led to the substantial developments in micro-fluidics. The general micro-fluidic component consists of micro-pumps, micro-valves, transport channels, heating/cooling devices, rate detectors and analytical devices. Integration of these elements in microfluidic systems has important application including the micro-total analytical system (μTAS) [1].

Several key issues in existing and emerging in micro-system are directly related to thermal phenomena. An overview of a subset of thermal issues in MEMS technology was reviewed by Don L. DeVoe [2]. The issues relating to fundamental limitation and opportunity in thermal micro-system were also presented in this paper.

Since PCR (polymerase chain reaction) concept was introduced in the early 1990s, miniaturization of PCR is the major issue to enhance the analysis process, such as fast thermal cycle time, low sample consumption, high sensitivity, portability [3,4].

Yang *et al.* [5] investigated several thermal boundary conditions numerically to construct a cost effective CR chip and analysis devices. Geometric optimization is also carried out to further improve thermal performances.

Edwards *et al.* [6] introduce a micro-fabricated thermal field flow fractionation (μTFFF) system with potential use as an integrated sample preparation system in (μTAS).

While precise heating control is essential in various thermal systems, existing commercial heaters are in adequate because of their large size and low thermal response. Therefore a built-in thin film μ-heater fabrication is needed in micro-system and optimal design of μ-heater is important process in advance of the integration of the component.

Precise flow control in micro-fluidic system is also challenging issue in MEMS device. Micro-flow sensors are one of the important components for controlling fluid flow in a micro-fluidic system. A thermal flow sensor generally consists of a heater and one or more temperature sensors [7]. The effects caused by heat transfer are evaluated in different ways, which correspond to the operating modes of a thermal flow sensor. Hot -wire sensor is thermal flow sensor that measures the effect of the flowing fluid on a hot body. The calorimetric sensor is widely used for mass flow controller that measures the asymmetry of temperature profile around the heater.

MEMS technology has been used to develop microsensors [8] with high sensitivity, low power consumption, and short response time.

Van der Wiel *et al.* [9] reports on modeling and characterization of liquid velocity disposable sensor needed in the biomedical field for measuring velocity in the range up to 2 m/s.

Kersjes *et al.* [10] developed miniaturized sensor mounted into catheter of 2 mm diameter for measurements in human blood vessels. For most applications mentioned above, rather small liquid velocities have to be measured. Governed by their small geometry, the biggest advantage of micro sensors are the low energy consumption, the ability to measure very small flow rates on the order of micro liters to nano liters per minute.

A measuring resolution can be achieved up to volume flow of 0.6 mliter/min (flow velocity u_{in} = 20 mm/s) with a channel of 1000 μm × 500 μm [11].

Recently, Gaitan and Locascio [12] present a demonstration of flow sensing in microchannel molded in PDMS using embedded IC-based microheating elements. This result indicates that thermal sensor is capable of measuring fluid flow

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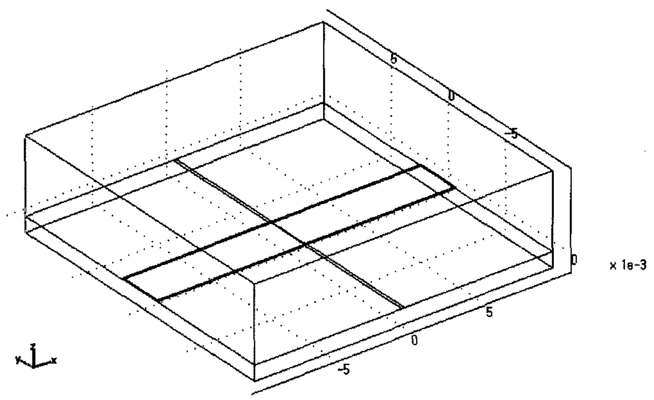

Fig. 1. Schematic of micro-channel based flow-sensing configuration.

with a lower flow detection limit of approximately 320 pL/s.

Our work focuses on a lower flow rate up to about 24 pL/s. In this paper, heat transfer simulation has been performed to obtain the optimal parameter to design the thermal flow meter and explain the thermal behavior of the flow meter. A short description of electric characteristics of ITO sputtered heater is presented. The effects of thermo-physical properties of materials, geometrical structure and boundary condition on the thermal performance are also investigated.

2. Model of System and Heating Elements

Fig. 1 illustrates the heating element integrated to a microchannel fabricated on PDMS and glass substrate for the micro-channel based flow sensing. The model can be fabricated through the following processes. 1) To start, the ITO (indium-tin oxide) layer is deposited on to a patterned glass with 1000Å thickness as a heating element. 2) Microchannel can be fabricated by pouring the uncured polymer, PDMS (polydimethylsiloxane), over the mold with extruded feature for the microchannel to a thickness of approximately 5 mm, and cured at room temperature. 3) After curing, cut to 2 cm × 2 cm square cover and peeled away from the mold. 4) PDMS cover with micro-channel is bonded and sealed to heater embedded glass for complete package. Capillary inter-connection for the fluid supply is not considered in this numerical simulation.

As current has passed through the heater, part of the heat generated in the heater dissipated through the substrate, covering materials, and rest of it convected out through the

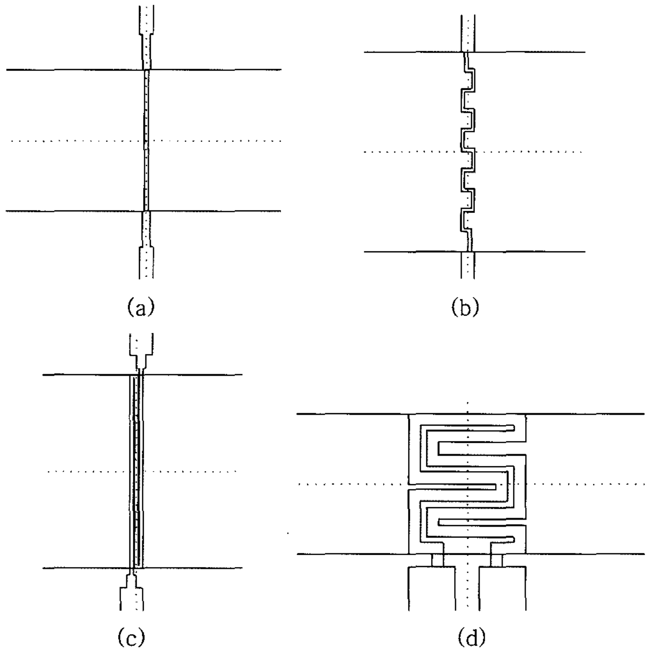

Fig. 2. Heating elements with ITO resistor and micro-channel on the glass substrate.

channel exit. Several types of heating elements are investigated as shown in Fig. 2 to find out the available heater capacity in this study. Fig. 2(d) is very small heating element (240 μm × 200 μm) designed for special reason. The designed micro-heating elements can be fabricated by sputtering the newly developed material ITO on the glass substrate. ITO film has been widely used as a heater when the flow visualization is needed due to its of highly transparent (85%) and low resistivity (5×10^{-4} Ωcm) [13]. The electric characteristics of heaters investigated are summarized in Table 1.

3. Numerical Process

Assuming laminar incompressible flow, and the flow velocity in the high aspect ratio (w/b = 30) channel flow profile can be two dimensional and obtained analytically. Then, we employed the commercial finite element software COMSOL 3.2 [14] to solve the multi-physics (electric and heat transfer) problem. Electromagnetic module is adopted to calculate the distribution of resistive heating (W/m^3) of heater. The electric potential is used as a boundary input in this module. Very thin heater

Table 1. Electric characteristics of heaters

	Width (μm)	channel width (mm)	resistance (Ω)	current (mA) E = 20 volt
Model 1	400	3	375	56
Model 2	200	3	750	28
Model 3	100	3	1500	14
Model 4	50	3	3000	7
Model 5	50	3	4600	4.4
Model 6	50	3	9000	2.3
Model 7	50	0.2	4000	5

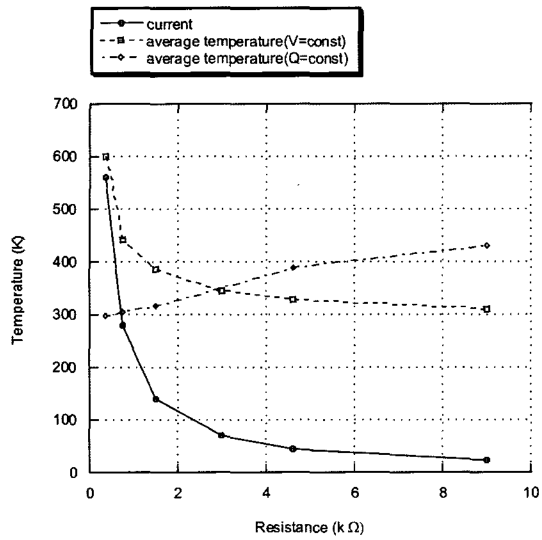

Fig. 3. Variations of temperature and current for heater resistance.

results in many troubles especially in meshing process. The shell-conductive media DC mode was applied to avoid this difficulty. It solves on 2D surface with highly conductive layer in a 3D geometry. The results of this module can be used as a boundary condition of heat transfer module to calculate thermal behavior of microchannel and its package.

4. Results and Discussion

As a pre-processing for the design of flow induced flow meter, effects of several design parameters such as optimal condition of heating element (geometry, size, power) and operating condition need to be investigated.

Fig. 3 illustrates average temperature of heating elements for various resistances (heating geometry). The currents induced by the resistance and given electric potential are also shown at the same plot. The results indicate that heater temperature and current decreases as the resistance increases for given electric potential (E = 20 volt). However note that the average temperature increases with resistance for constant power input (Q = VI = 0.14 W). We can use the results of this plot as a map representing the range of allowable electric potential and current. Range of heater temperature also can be approximated along with a given heater size.

The thermo-physical properties of the substrate and cover of the channel can make strong effect on the channel flow. Fig. 4 represents the effect of packaging materials on the temperature of channel wall along the distance of flow direction. Heater is located at the center of channel, i.e. x = 0.01 m. The inlet velocity u_{in} = 0.001 m/s, electric potential 20 volt, straight heater and convection boundary condition keep constant value. In this plot two representative materials widely used in micro-fluidic system are compared. PDMS has become popular as an inexpensive and easily molded material for micro-fluidic devices because it has a number of useful properties: low cost, low toxity, transparency for visible wavelength, and chemical inertness [15]. Glass is traditional material for in chemical

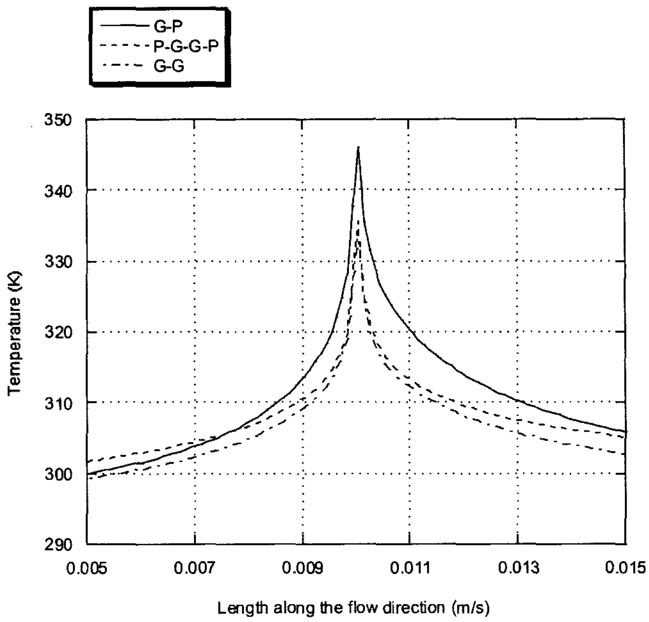

Fig. 4. Effect of packaging materials on the substrate temperature.

analysis. The low electrical conductivity makes glass the perfect material for capillary electrophoresis. The simple machining technique using wet etching in buffered hydrofluoric acid (HF) makes glass an attractive material for many analysis devices. The first capital represents substrate material while the second identifies the material covering the channel. Glass-glass bonded (G-G) channel may be fabricated easily by using the double adhesive tape. Even the inlet velocity is quite low (u_{in} = 0.001 m/s), the convection flow effect results in the increase in the temperature about 1.0% at a location of ±1 mm apart from the heater representing asymmetric temperature distribution. This tendency represents the fact that this system can be used as a means to measure the flow induced thermal flow sensing apparatus. P-G-G-P represents the model of G-G enclosed by the PDMS. The PDMS play a part in the thermal barrier this case due to its low thermal conductivity and overall temperature increased along the channel. G-P bond is the packaging that the channel is directly fabricated in the PDMS by soft lithography method, which can be used for rapid type microfluidic devices. Replica molding can be used for fabrication of microchannels [1]. Dominant increase in the maximum temperature is shown near the heater. We can imagine the low consumption of power and more sensitive apparatus can me obtained by this configuration.

The package supposed to be exposed to various types of external thermal conditions. In general, those thermal boundary conditions can also greatly affect the thermal performance of the system. Fig. 5 shows the effect of thermal boundary conditions on the substrate temperature. As the heat dissipation increased through the enclosing walls like constant wall or convection boundary conditions, the temperature distribution of channel flow is less sensitive to the supplied power input. It is also shown that the overall temperature and maximum temperature near the heater increased by insulating the ambient

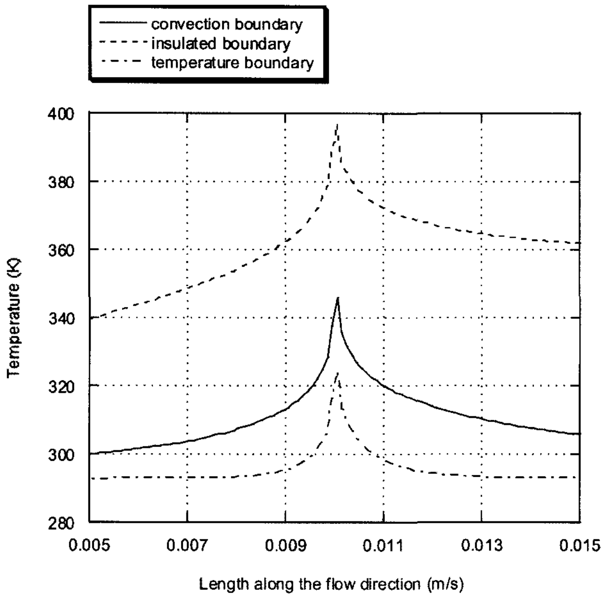

Fig. 5. Effect of thermal boundary conditions on the substrate temperature.

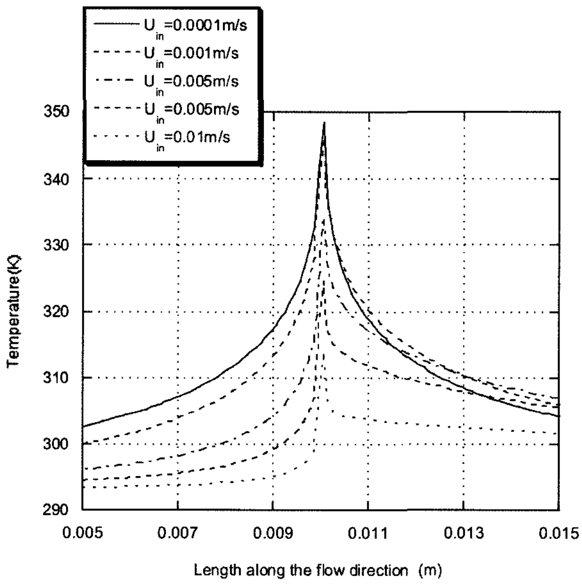

Fig. 6. Temperature distributions along the flow direction (h = 20 W/m²K).

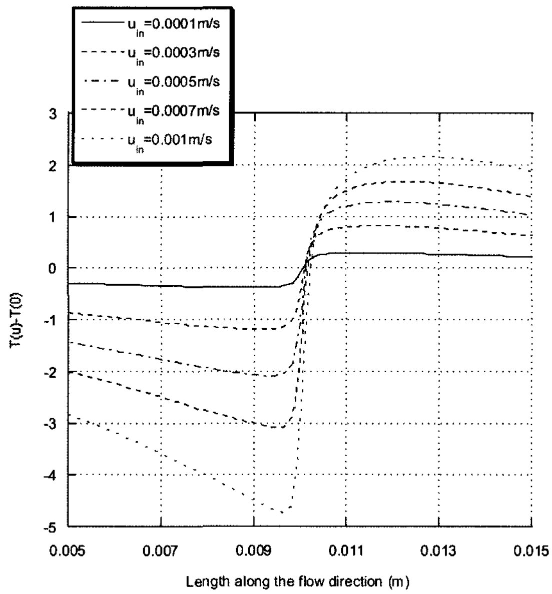

Fig. 7. Temperature change along the flow direction (h = 20 W/m²K, E = 20 volt).

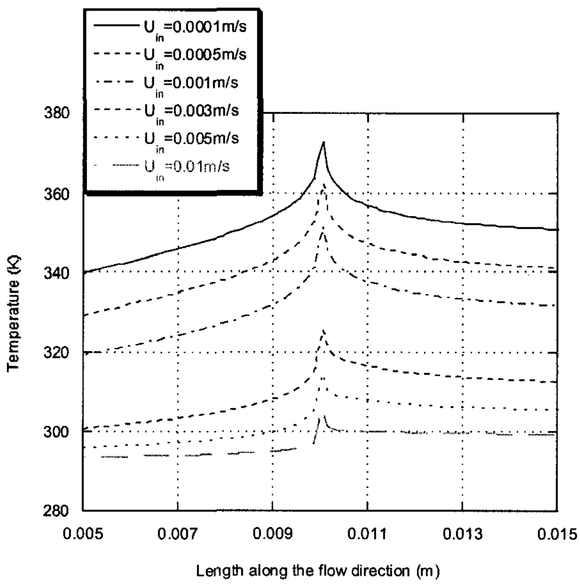

Fig. 8. Effect of flow rate for the insulated boundary (E = 15 Volt).

walls. It is clear that flow sensitive temperature variations can be expected by this condition. However note that actual experimental scenario may be lies between this two limited cases.

For a given geometrical and thermal conditions, the effects of flow rate on the thermal performance is the essential part for the application of micro-channel based flow sensing apparatus. The curves in Fig. 6 characterize the effect of inlet velocity on the axial temperature distribution along the flow direction. In the case of near zero inlet flow (u_{in} = 0.001 m/s), the temperature profile is symmetric around a heater location. For low flow velocities, the upstream (x<0.01 m) temperature is relatively high due to the diffusion dominant flow. However, as the inlet flow rate increases diffusion is not allowed to the upstream flow and become convection dominant at far downstream of the flow.

The temperature change due to flow rate, $\Delta T = T(u) - T(0)$, is plotted in Fig. 7. The basic principle of the fluid induced flow sensor is to use the convection heat transfer from heater to liquid flowing inside a microchannel. Note that as the velocity increases, ΔT approaches its maximum away from the heater, which shifted to the downstream of the flow. The negative temperature change at higher flow velocity represents an increased cooling of diffusion region downstream of heater. Opposite signs of upstream and downstream can be useful information for the detection of flow direction.

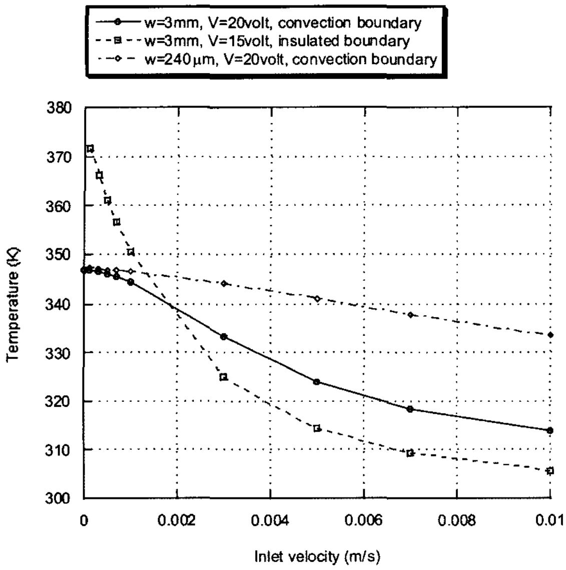

Fig. 9. Fluid flow effect on the temperature of heater.

Temperature distribution in the middle of the channel as a function of the position x is shown in Fig. 8 for insulated boundary condition. It is clearly shown that with insulation boundary, the temperature upstream of the channel increases considerably, especially in the low flow rate region. Even the supplied electric potential is reduced to 15 volt (25% decreases from 20 volt), the maximum temperature increases up to 351 K (approximately 8.3% increase at u_{in} = 1 mm/s) compared with constant wall boundary condition. The results indicate also the temperature distribution varies consistently with inlet velocity along the whole length of the flow direction, which imply the better relationship between flow rate and temperature difference.

Since the heater temperature reflects flow rate, it can be expressed as a function inlet velocity. The average temperature of heater corresponding to the inlet velocity is plotted in Fig. 9. As the inlet velocity increases, the average heater temperature decreases. From this plot, it can be observed that the temperature variation is not sensitive enough for low inlet velocity in the range of u_{in} <0.001 m/s with convection boundary condition. It is clear that this sensitivity can be improved by insulating the wall boundary. It is also important that the relationship between flow rate and heater temperature can be linear by using the micro-heater embedded in micro-channel of 240 μm width. The results also indicate that designed thermal sensor is capable of measuring pL/s order flow rate (i.e. 24 pL/s with u_{in} = 0.001 m/s).

5. Conclusion

A three dimensional numerical method was used to simulate for the design of micro-flow induced thermal sensor which is capable of measuring fluid flow with a lower flow detection limit of approximately 24 pL/s.

Electric characteristics of ITO sputtered heater were presented in this study, which can be used as a map of heater design in the range of available system temperature.

The effect of thermo-physical properties of materials, geometrical structure and boundary condition on the thermal performance was investigated. The thermal flow meter, which has a linear relationship between flow rate and heater temperature, was also proposed in this study.

The results in this study are obtained by using the ideal conditions. For practical applications there will exist some technical limits for fabrication of micro-size heater and channel. However, the results will provide the information for the available design of flow sensing elements.

Acknowledgments

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References

1. Nguyen, N. T., Wereley, S. T., "Fundamentals and Applications of Microfluidics," Artech House, INC., 2002.
2. DeVeo, D. L., "Thermal Issues in MEMS and Microscale Systems," IEEE Transactions On Components And Packaging Technologies, Vol. 25, No. 4, pp. 576-583, 2003.
3. Lin, Y. C., Yang, C. C, Huang, M. Y., "Simulation and experimental validation of micro polymerase chain reaction chips," Sensors And Actuators B 71, pp. 127-133, 2000.
4. Zou, Z. Q., Chen, X., Jin, Q. H., Yang, M. S., Zhao, J. L., "A novel miniaturized PCR multi-reactor array fabricated using flip-chip bonding techniques," J. Micromech. Microeng. 15, pp. 1476-1481, 2005.
5. Yang, M., Pal, R., Burns, M. A., "Cost-effective thermal isolation techniques for use on microfabricated DNA amplification and analysis devices," J. Micromech. Microeng. 15, pp. 221-230, 2005.
6. Edwards, T. L., Gale, B. K., Frazier, A. B., "A Micromachined Thermal Field-Flow Fractionation System," in Proc. of Transducers '99, pp. 742-745, 1998.
7. Elwenspoek, M., Wiegerink, R., "Mechanical Microsensors," Springer.
8. Qiu, L., Hein, S., Obermeier, E., Schubert, A., "Micro gas-flow sensor with integrated heat sink and flow guide," Sensors and Actuators A 54, pp. 547-551, 1996.
9. van der Wiel, A. J., Linder, C., de Rooij, N. F., Bezinge, A., "A liquid velocity sensor based on the hot-wire principle," Sensors and Actuators A, 37-38, pp. 693-697, 1993.
10. Kersjes, R., Liebscher, F., Spiegel, E., Manoli, Y., Mokwa, W., "An invasive catheter flow sensor with on-chip CMOS readout electronics for the on-line determination of blood flow," Sensors and Actuators A 54, pp. 563-567, 1996.
11. Lammerink, T. S. J., Tas, N. R., Elwenspoek, M., Fluitman, J. H. J., "Micro-liquid flow sensor," Sensors and Actuators A, 37-38, pp. 45-50, 1993.
12. Gaitan, M., Locascio, L. E., "Embedded Micro-Heating Elements in Polymeric Micro-Channels for Temperature Control and Fluid Flow Sensing," J. Res. Natl. Inst. Stand. Technol. 109, pp. 335-344, 2004.
13. Narshimha Rao, K., "Preparation of transparent conductive oxide films by activated reactive evaporation," OPT. Eng. 41(11), pp. 2705-2706., 2002.
14. COMSOL Multi-physics 3.2 user's guide 2005.
15. A. M. Christensen, D. A. Chang-Yen, B. K. Gale, "Characterization of interconnects used in PDMS microfluidic systems," J. Micromech. Microeng. 15, pp. 928-934, 2005.